Atomic Disenchantment

A Global History of Nuclear Energy



Per Högselius

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Atomic Disenchantment

A Global History of Nuclear Energy

Per Högselius

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Series Foreword

Energy lies at the heart of anthropogenic climate change and ecological crises. Yet energy is too often treated as a material resource that is mostly external to morality, politics, or culture. Policymakers struggle to understand the complexity of energy transitions when they approach energy as a matter for technoscientific experts. Energy systems are both material and social, affecting everything from how people work, to their fantasies of the good life and the design of their cities. As a result, changing how people use energy—and how much they use—involves more than calculations of price or motive power. Fortunately, the past decade has witnessed a remarkable efflorescence of research exploring the significance of energy for history, politics, society, and culture. This series, Critical Energy Studies, showcases the very best critical research on energy being conducted today in the arts, humanities, and social sciences. A critical approach to energy not only helps us to understand modern life, in the best humanistic tradition, but is also necessary for engineers, activists, or policymakers who want to solve energy problems.

Critical Energy Studies looks backward and ahead, and across continents, pursuing inquiry into the coal, oil, and nuclear energy complexes that shaped modernity, as well as to future forms of decarbonized sociality in-the-making. Energy is capacious; following energy means crisscrossing traditional boundaries of nations, bodies, or species and rethinking geographic scales of local, regional, and global. Books in the series will reflect this reach, pursuing innovative investigations of energy with respect to themes of race and ethnicity, sexuality, religion, political imaginaries, labor, social and environmental justice, decolonization, indigeneity, identity and belonging, technology and science, media and communication,

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urban studies, and renewable futures. The series is also open to more speculative projects that map out alternative social and cultural futures that could follow decarbonization of the global economy. Beyond its academic goals, Critical Energy Studies amplifies critical investigations into ways of living with energies past, present, and future—research essential to inform sociopolitical and culture change in support of climate action and energy transitions.

As one of the most consequential yet paradoxical energy technologies of the modern era, an investigation of nuclear power requires the kind of critical, interdisciplinary research we hope will define all the books in Critical Energy Studies. In *Atomic Disenchantment: A Global History of Nuclear Energy*, the second book in our series, Per Högselius offers a sweeping history of nuclear energy's spectacular rise and fall (and potential rise again). His account follows nuclear energy across three spatial registers—the "nuclear steam engine," a Faustian grafting of bomb-making science onto nineteenth-century technologies of steam power; "wet nuclear extractivism," which tied reactors to rivers, lakes, and seas, with often disastrous social and ecological consequences; and the pursuit of a nuclear circular economy, whose failures around waste have generated enduring crises of legitimacy. By reframing the history of the atom in terms of these troubled marriages between new and old, infinite and finite, Högselius dismantles the enduring myth of nuclear power as an inherently modern, scientific, and potentially utopic form of energy. Instead, he shows that nuclear energy's fate—its stalled transitions, recurring accidents, and unresolved waste dilemmas—can only be understood through the contradictions it inherited from earlier energy regimes. This is energy history at its best—conceptually bold, empirically rich, and urgently relevant to ongoing debates about the direction energy transition should take.

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Acknowledgments

This book has at least three origins. One is my year-long stay in Greifswald, a sleepy university town on the Baltic coast of Germany, as a student almost thirty years ago. That's where I first encountered atomic disenchantment. Greifswald was the atomic capital of East Germany and home to a massive nuclear power plant with eight Soviet-designed reactors. Five of these reactors were operational before Germany's reunification in 1990. Then, the plant was abruptly and prematurely closed. I came there to write a master's thesis about the facility's rise and fall, trying to understand why Greifswald's nuclear history did not turn out as the country's nuclear proponents had hoped. That's essentially the same question I explore in this book, though on a global scale: Why did nuclear power fail to become the dominant energy source envisioned by postwar atomic visionaries?

Another origin of the book is my earlier historical exploration of the nuclear fuel cycle and, in particular, the variety of national trajectories that populate the history of spent nuclear fuel. I was fascinated by the vision of a nuclear circular economy, enabled by radiochemical reprocessing technology coupled with the dream of the fast breeder reactor, which, in theory, could produce more fuel than it consumed. Once again, I was struck by the contrast between the grandiose promises and expectations and the harsh realities on the ground, where so many obstacles appeared in actors' struggle to forge a closed nuclear fuel cycle.

The third and final origin of *Atomic Disenchantment* is the NUCLEARWATERS research project, which I led from 2018 to 2024. Funded by the European Research Council (ERC; grant number 771928), this project allowed my colleagues and me to explore the history of nuclear power as a history of water and steam. NUCLEARWATERS taught me to view nuclear

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technologies as the outcome of fascinating hybridization processes in which nuclear science merged with older technological traditions, such as steam engine construction and classical hydraulic engineering. It seemed to me that such encounters between the new and the old could help us understand why nuclear power, despite some very attractive features, never really conquered the world in the way early atomic visionaries dreamed.

I'm grateful for the ERC's financial support. Without it, this book could not have been written. Thanks to the project and grant, I was able to spend several years exploring the global history of nuclear energy in a cooperative way with brilliant colleagues and friends: Kati Lindström, Anna Storm, Alicia Gutting, Achim Klüppelberg, Siegfried Evens, and Roman Khandozhko. I also learned a lot from numerous guests that visited our group and participated in our project activities: Louis Fagon, Andrei Stsiapanau, Melina Antonia Buns, Stefan Guth, Dima Litvinov, Robert Jacobs, Sonali Huria, Tijana Rupčić, Hannah Klaubert, and Fannie Frederikke Baden. A highlight was a workshop on the "nuclear-water nexus," held in June 2022 with thirty-two participants from different parts of the world. It became the basis for an edited volume published by the MIT Press in 2025.

My academic base has been the Division of History of Science, Technology and Environment at KTH Royal Institute of Technology in Stockholm. For a nuclear energy historian, I could not imagine a better place. I have benefited greatly from my daily interactions with my curious and innovative colleagues, as well as with my students. Another place that has almost felt like home during these years is the Hanse-Wissenschaftskolleg in Delmenhorst, Germany, where I have attended recurring meetings of the Energy Materiality Study Group twice a year for the past few years.

I would like to thank my colleagues at home and abroad who have taken the time to read and comment on earlier drafts of sections and chapters: Margarita Balmaceda, Corey Johnson, Heiko Pleines, Doug Rogers, Veli-Pekka Tynkkynen, Teva Meyer, Arne Kaijser, Siegfried Evens, Jan-Henrik Meyer, Astrid Mignon Kirchhof, Anna Storm, Sonja Schmid, Anaël Marrec, Matti Kojo, Jonas Anshelm, and, last but not least, Iva Lučić. Two anonymous reviewers helped me improve the manuscript as a whole. I am also grateful to the editors of the Critical Energy Studies series and to Beth Clevenger at the MIT Press for their comments, ideas, and encouragement. Needless to say, I am solely responsible for the shortcomings of the final manuscript.

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Some parts of the book have an earlier publication history. Hence chapter 2, "Envirotechnical Entanglements," includes material previously published in Per Högselius, "Atomic Shocks of the Old: Putting Water at the Center of Nuclear Energy History," *Technology & Culture* 63, 1 (2022): 1–30.

In chapter 5, "The Global Stagnation," the section "The Collapse of the Communist Atom" is based on Per Högselius & Achim Klüppelberg, *The Soviet Nuclear Archipelago: A Historical Geography of Atomic-Powered Communism* (Budapest: Central European University Press, 2024).

In chapter 6, "The Renaissance That Wasn't," the section "Nature Strikes Back: Nuclear Energy in an Age of Climate Change" is adapted from Per Högselius, "Atomic Shocks of the Old: Putting Water at the Center of Nuclear Energy History," *Technology & Culture* 63, 1 (2022): 1–30 and Per Högselius, "Introducing the Nuclear-Water Nexus," in *The Nuclear-Water Nexus,* edited by Per Högselius and Siegfried Evens (Cambridge, MA: MIT Press, 2025).

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Introduction

For as long as I can remember, I have been fascinated by nuclear energy. It must have been in high school, or maybe even in elementary school, that I first learned about uranium and its hidden powers, how atoms could be split and release energy in the process, and how a stream of neutrons made it possible to sustain a chain reaction that could be both fast and slow—fast, like in bombs, or slow, like in a reactor. I was impressed by both, but especially by the slow, controlled way of putting the atom to work. I imagined serious, clean-shaven men in white suits in the control room, using their scientific knowledge to harness the atomic nucleus and the energy it would release; the latter could be calculated using Einstein's famous formula $E = mc^2$. It was such a radically different—and, as it seemed, obviously superior—approach to energy production compared to other, more traditional methods, such as burning firewood, dung, or coal.

I remember a caricature that was published in a newspaper. On the left, muscular workers in dirty clothes shoveled tons of black fuel into a coal oven where a huge fire raged. On the right was a bespectacled man in a gleaming white lab coat. He picked up a uranium pellet with what looked like a pair of medical tongs and placed the tiny piece of nuclear fuel into a reactor made of stainless steel. The message was clear: Atomic energy was more scientific, more technologically advanced, and more civilized than other energy sources. Above all, uranium fuel boasted an extremely high energy density: A single uranium pellet generated more energy than a ton of coal![1]

In the early days of nuclear engineering, such illustrations were accompanied by bold yet seemingly plausible claims that splitting atoms to generate electricity would be extremely cost-effective. In 1954, Lewis Strauss, the

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chairman of the US Atomic Energy Commission, famously predicted that nuclear energy would be "too cheap to meter"—a controversial claim but one that reflected the optimism of the time. Fossil fuels would hardly be able to compete for much longer.[2] Moreover, atomic energy was portrayed as the cleanest source of electricity the world had ever seen. Burning coal and oil was known to cause immense environmental and health problems, and hydroelectricity destroyed riverine ecosystems. The rise of nuclear power meant that these problems would be a thing of the past. Overall, atomic energy would help the world "move forward toward peace and happiness and well-being."[3]

It is not difficult to understand, then, why governments were eager to promote nuclear energy. Throughout the 1950s and 1960s, state actors around the world invested billions of dollars in the atom. Some of these efforts were overtly or covertly motivated by an interest in acquiring nuclear weapons, but the civilian promises of nuclear engineering were never far behind. Not only the great powers but also a range of smaller countries devoted a large proportion of their public research budgets to developing nuclear science and technology. They felt they could not afford to be left behind. Nuclear engineering was seen as the next "generic," or general-purpose technology, with potentially revolutionary applications not only in heat and electricity production but in transportation, agriculture, water supply, civil engineering, and more. Nuclear technology promised to propel humanity forward in its quest for energy and power, on par with the invention and spread of the steam engine in the years around 1800 and the internal combustion engine a century later.[4]

Yet nuclear power's real-world career did not turn out as successful as the visionaries of the 1950s had hoped. The atom ultimately failed to become the ubiquitous technology that many had anticipated. Over time, its intended role shrank, and it was eventually used almost exclusively for electricity generation. Even in that field, however, the atom did not succeed in acquiring a dominant position. Today nuclear energy accounts for a meager 9 percent of the world's electricity supply, and it contributes less than 4 percent of total primary energy.[5] In only a few national contexts has it replaced other energy sources.

Most surprisingly, nuclear power failed to outcompete coal. Despite coal burning's seemingly inferior scientific basis and the extreme discrepancy in energy density, the coal industry proved far more successful than nuclear energy in providing the world with cheap electricity and heat. Societies also

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continued to consume more energy by burning oil than by splitting atoms. Likewise, natural gas has become a more important energy source than nuclear energy—despite the immense logistical challenges and high costs of building pipeline systems from faraway gas fields to major consumption hotspots. Global investments in hydropower also outpace those in nuclear energy. In the twenty-first century, wind and solar energy follow in the footsteps of fossil fuels and hydropower, growing rapidly from year to year as a source of electricity production. Meanwhile nuclear energy continues to lag far behind in the global energy mix (figure 0.1).

For a brief period in the late 1960s it did seem as if nuclear energy were on the verge of a spectacular breakthrough. More and more electricity-generating reactors were ordered, and many nuclear power plants began construction in the United States, Europe, the Soviet Union, Japan, and elsewhere. Already in the mid-1970s, however, this trend came to an end, and the enthusiasm for nuclear energy waned almost everywhere (figure 0.2). Today most new nuclear power plants are built in China, but even there the atom is nowhere close to becoming a dominant energy source.

In the early days of nuclear power, there was also the vision that atomic energy would spare societies from the political and social controversies that had accompanied fossil fuels and hydropower. There would be no disruptive booms and busts, nor any labor disputes. Internationally, the atom would relieve Cold War tensions as capitalist and socialist governments alike embraced nuclear science and its many peaceful applications. Additionally, nuclear power would stimulate cooperation between the Global North and the Global South. It would "provide abundant electrical energy in the power-starved areas of the world," thus putting an end to earlier global energy injustices.[6]

Ultimately, these visions did not come to fruition. In fact, more than any other energy source, the atom fueled controversy and led to some of the most intense social and political struggles in modern history. The potential health and environmental effects of thermal and radioactive pollution, coupled with the fear of nuclear disasters, sparked conflict worldwide. Tellingly, political scientists turned the antinuclear movement into a paradigm case for New Social Movement theory,[7] while the perception of nuclear energy as a dangerous, Faustian technology inspired scholars to formulate new social theories of risk.[8] In numerous countries, conflicts over nuclear power decisively shaped the political landscape. Internationally, nuclear

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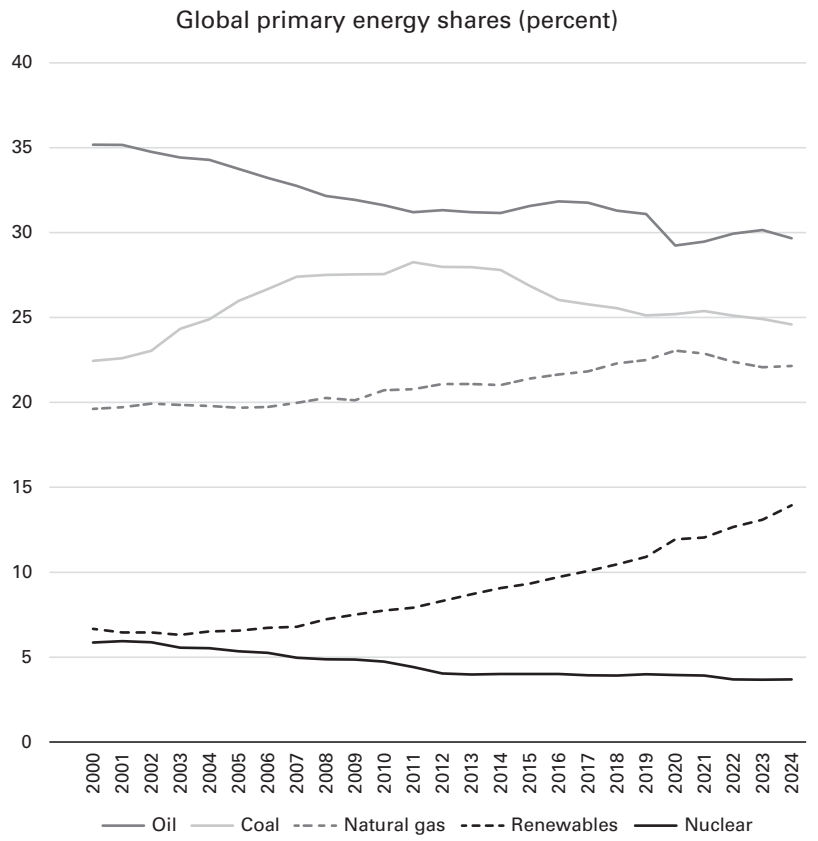

Figure 0.1
Global primary energy shares, 2000–2024 (percent). Renewables include hydropower, wind, solar, modern biofuels, and other renewables (but not traditional renewables). *Source*: Author's own graph based on data from Hannah Ritchie and Pablo Rosado, "Global Primary Energy Consumption by Source," 2025, https://ourworldindata.org/energy-mix.

power exacerbated North-South tensions, as the Global North grew increasingly wary of sharing key nuclear technologies with the Global South.

For someone passionate about physics and atoms, this historical outcome is disappointing and frustrating. The idea is so appealing: splitting atoms to generate immense amounts of energy with minimal uranium input and minimal environmental pollution. One single uranium pellet, "the size of your fingertip," can generate as much energy as a ton of coal. There is

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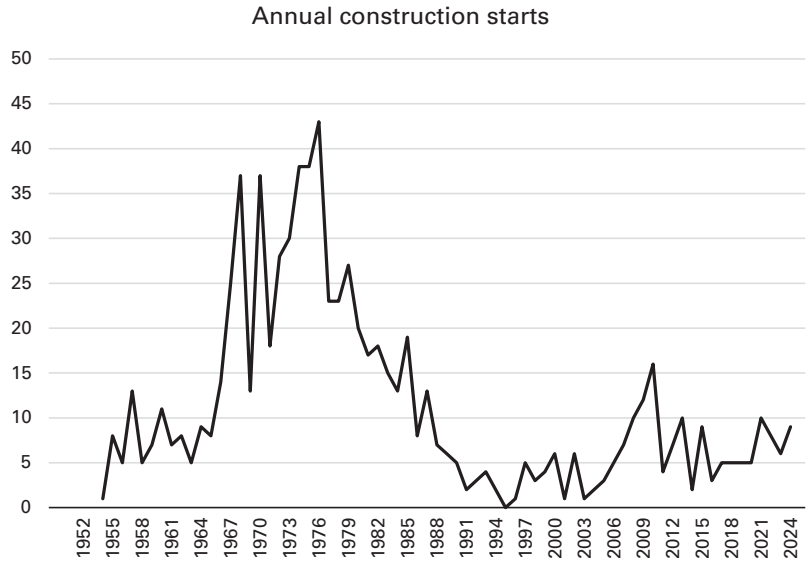

Figure 0.2
Annual number of reactor construction starts, 1954–2024. *Source*: Author's own graph based on International Atomic Energy Agency (IAEA) data.

something undeniably impressive about this. And yet nuclear power nowadays contributes less than one-tenth to global electricity production, and it lives its life in the shadow of massive investments in fossil fuels and renewables. Most countries of the world do not rely on nuclear energy at all. Why did the attempts to make the atom a dominant energy source fail? That's the main question this book sets out to answer.

Explaining Nuclear Power's Failure

Analysts have offered numerous possible explanations for why nuclear energy never managed to become a dominant energy source. Industry insiders and other advocates of nuclear power usually blame the atom's disappointing performance on poor politics and irrational fears. They argue that nuclear energy is "the safest large-scale energy source" and not, as the critics insist, the most dangerous.[9] Such misconceptions are seen to have fueled sensationalist media reports and influenced political decision-making. Compared to the fossil fuels, nuclear power has caused a negligible

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number of deaths. Accordingly, the rigorous safety requirements that burden the nuclear industry are unnecessarily conservative—and they have made nuclear energy artificially expensive. "Exaggerated fears," as MIT professor Kerry Emanuel puts it, have made nuclear power "too costly and unpopular to develop and deploy in much of the world."[10]

Critics oppose this view, arguing that nuclear energy has failed due to its inherent flaws and nuclear engineers' inability to devise effective solutions, especially for safety issues.[11] Henry W. Kendall, a founding member of the Union of Concerned Scientists, claimed that "some early bad choices were made" and that the light-water reactors that came to dominate the global nuclear industry "were unforgiving in operation and so hard to make safe."[12] Echoing this line of reasoning, German historian of technology Joachim Radkau suggests that nuclear energy *could* have succeeded if the leading actors had taken the time to thoughtfully consider the available technological choices. He points to a number of "repressed alternatives" in the history of nuclear power, spotlighting a number of reactor designs that look sounder and less risky than those that were ultimately adopted.[13] Others have posited that the sheer complexity and scale of nuclear power plants doomed nuclear energy to failure. Sociologist Charles Perrow pointed to nuclear power plants as a paradigmatic case of "tightly coupled systems," in which accidents are constantly waiting to happen. Perrow developed his theory of such "normal accidents" in the aftermath of the partial meltdown at Three Mile Island's second reactor in 1979.[14]

A common perception is that nuclear energy has failed precisely because of several serious accidents, including those at Three Mile Island, Chernobyl (1986), and Fuskushima (2011). This narrative is offered not only by journalists and other nonacademic observers but also by leading environmental scholars such as John McNeill and Peter Engelke.[15] At first glance, this line of argument seems to make a great deal of sense. It seems logical that serious accidents halt the further spread of a technology. Yet a closer look reveals that the nuclear industry was already heading toward stagnation *before* 1979. In fact, there were clear signs of stagnation in many countries soon after the onset of the 1973/1974 oil crisis. In other words, nuclear energy stagnated even though the price of one of its most serious competitors quadrupled! This seems counterintuitive but holds true for all but a few countries.

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Some studies explain nuclear power's failure to achieve dominance by pointing to broader economic and technological trends. For example, a study by the Organization for Economic Cooperation and Development's (OECD's) Nuclear Energy Agency (NEA) argues that falling oil prices in the 1980s removed many governments' incentives to support nuclear expansion. Lower than expected electricity demand growth reduced the need for new nuclear plants further, and high interest rates discouraged investment in nuclear power as a capital-intensive technology. Meanwhile, the development of the combined cycle gas turbine—an important innovation—and an increased availability of natural gas spurred a transition to gas in the electricity sector.[16] This is an interesting line of argument, but it also raises new questions. For instance, why were nuclear power plants, with their incredibly high energy density, so susceptible to price fluctuations in the oil and gas markets? And why did nuclear energy evolve to become such a large-scale, capital-intensive technology when modern gas power plants could be built economically on a much smaller scale?

The high costs of nuclear construction have been much debated in recent years. They are widely seen as having contributed to nuclear power's failure to become a more widespread source of energy. Echoing Perrow's notion of nuclear power plants as tightly coupled systems, critical authors such as Arnulf Grubler, Jonathan Koomey, and Nathan Hultman point to the growing size and complexity of reactors as a fundamental problem. The quest for economies of scale, they argue, generated a negative learning curve. Over the years, this led to longer construction times, which in turn ballooned the costs due to interest and labor.[17] Thomas Wellock adds nuance to this discussion by highlighting how uncertainty about accident risk and the evolution of regulatory requirements underpinned delays and cost escalations.[18] Meanwhile, authors such as Steve Cohn have argued that nuclear power has never been competitive because it has always depended on government subsidies and other forms of support.[19] Accordingly, nuclear programs have often eroded when fully exposed to market forces.[20]

Another common theme is the close relationship between nuclear energy and nuclear weapons. The military origins of atomic energy are well known, and civilian and military forms of nuclear engineering have continued to interact ever since. This Janus-faced nature of the atom has made it difficult for nuclear engineers to gain full acceptance for their expansive visions. It has historically fueled public opposition to nuclear

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power and hindered the transfer of nuclear technology. The challenge of "containing" the military atom through international regulatory measures has proven formidable. Especially in the Global South, as historian Jacob Darwin Hamblin notes, this has made it utterly difficult to exploit the "peaceful" atom.[21]

Antinuclear movements are widely recognized for playing a decisive role in slowing and countering nuclear expansion. Many analysts believe that without grassroots movements and social mobilization, nuclear energy would have become much more dominant in the global energy mix. By mobilizing "counter-expertise," antinuclear activists in North America, Western Europe, Asia, and elsewhere were able to challenge claims that nuclear power plants were completely safe, that their daily operations caused no environmental harm, and that storing nuclear waste posed no problems. The resulting clashes between experts with radically different views played out in public debates and in courtrooms. In numerous cases, such power struggles prevented tentative reactor projects from materializing or led to closure of operational plants.[22]

But why did so many people oppose nuclear power? The literature offers two competing explanations. Technically oriented authors, such as Vaclav Smil, view the emergence of antinuclear activism primarily as a natural reaction to "cost overruns in the construction of nuclear plants and a frustrating inability to come up with an acceptable way to store spent nuclear fuel" and "switch to reactors that might be safer."[23] Historians and social scientists, by contrast, have sought to reconstruct the fears and emotions underlying antinuclear activism on a deeper level. Historian of science Spencer Weart argues that "nuclear energy gradually became a condensed symbol for many features of industrial and bureaucratic authority (especially the horrors of modern war)." Images of reactors and radiation had "archaic connections stretching back to alchemical visions of transmutation," relating "less to technical facts than to deep-rooted concerns about authority and personal and social transformations."[24]

Scholars have also been keen to emphasize that antinuclear movements were part of broader struggles against capitalism, unbridled economic growth, and centralized states. In Eastern Europe, antinuclear activism morphed into anti-communist struggles for political independence from the Soviet Union. In Francoist Spain in the 1970s, as well as in Taiwan and South Korea in the 1980s, it became inextricably linked to local democracy

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movements. Following this line of analysis, antinuclear activism was merely a tool that actors mobilized to achieve other goals.[25]

Lastly, a number of studies have attempted to explain the failure of nuclear power as resulting from unique national circumstances. John Campbell, for example, points to the specific institutional structures of the United States as the fundamental reason behind the unexpected collapse of the US nuclear industry in the 1970s. The Americans, believers in the power of free market competition, were traditionally opposed to monopolistic trends. This made it difficult for nuclear builders to develop a standardized reactor type and size, which translated into cost disadvantages vis-à-vis fossil fuels. Opponents to nuclear power were also able to draw on "the relatively open nature of the US policy process at the level of implementation," which included siting and licensing hearings for individual power plants.[26]

Similarly, Germany's unique characteristics are often cited as the reason for the stagnation and subsequent phase-out of nuclear power in that country. Authors such as Dolores Augustine point to the distinctly German protest culture and citizen science, while Lutz Mez and Annette Piening demonstrate how Germany's particular governance style defined the negotiated lifetime-limit approach that characterized the *Atomausstieg*.[27] The United Kingdom's failure to develop cost-competitive nuclear power plants, for its part, has been interpreted in relation to Britain's perception of itself as a great power. This self-perception led to an unwillingness to adopt American light-water technology and a preference for expensive, domestically designed reactors.[28] The Soviet Union's failure to turn nuclear power into a dominant energy source is commonly explained by the inefficiencies of its centrally planned economy as well as a technological and political culture that allowed dangerous reactor designs to proliferate.[29] Greek historians, meanwhile, point to an unusually high level of seismic activity in their country as the key factor behind the lack of nuclear power plants there.[30]

Such nation-specific explanations may seem plausible and convincing when viewed individually. However, collectively, the fact that not only a few, but nearly all countries have failed to make nuclear power a dominant energy source indicates that national factors alone cannot explain this outcome. Clearly, something deeper is at play. Complicating matters further is the case of France, which suggests that it was not an impossible task to construct an electricity system that revolved almost entirely around the atom.[31]

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Atomic Shocks of the Old

Overall, nuclear power's "strange career," as John McNeill aptly dubbed it, remains both confusing and ambiguous. *Atomic Disenchantment* posits that shifting our perspective slightly may help us understand why the atom failed to become a dominant energy source. It argues that we need to take a step back from the more well-known themes in nuclear history, such as the debates about different reactor types, the impact of nuclear accidents, and social mobilization around the atom. Instead, we must zoom in on the clashes and contradictions that played out in the nuclear industry's attempts to connect with older technological traditions and practices. As we will see, the global history of nuclear energy becomes more comprehensible when viewed as an arduous effort to combine radical new nuclear-scientific insights with old, seemingly mundane technologies, including classical steam engines, ancient water withdrawal techniques, and traditional waste management and resource recycling methods.

The book draws inspiration from historian of technology David Edgerton's *The Shock of the Old: Technology and Global History Since 1900*, which highlights how an exaggerated emphasis on "innovation" in the analysis of technology obscures how older technologies continue to influence—and dominate—our societies and our human lives even in a supposedly high-technological age.[32] Economist Joseph Schumpeter's conceptualization of innovations as "new combinations" of already existing things is also useful for understanding nuclear energy in its historical context. No scientist, inventor, or engineer can escape the challenge of making the "new" fit with the "old."[33]

Scrutinizing the history of the civilian atom in its global context, the book shows how clashes between nuclear science and older technologies unfolded on three levels: micro, meso, and macro. At each level, nuclear science combined with existing traditions and practices to produce problematic outcomes. *Atomic Disenchantment* revolves around these three "marriages" between nuclear science and older, nonnuclear technologies.

The micro level refers to the internal workings of nuclear power plants. Here, the challenge was to combine the "new" phenomenon of nuclear fission with "old," already existing techniques of electricity generation. For this purpose, scientists and engineers with experience of nuclear weapons production joined forces with the fossil-industrial complex. They theorized

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that the military atom could be "tamed" by transferring the heat produced through nuclear fission to a boiler. There, a continuous flow of water would turn to steam, which could be fed into a conventional turbine and electric generator. A nuclear power plant would, in essence, become a powerful steam engine, thus linking up with a proud engineering tradition with roots in the eighteenth-century Industrial Revolution. Specifically, nuclear plant designers envisioned their plants functioning much like coal power plants.

Constructing such "nuclear steam engines," however, proved more challenging than expected. The uranium fuel's immense energy density resulted in much greater heat flows than in coal power plants, making nuclear power more difficult to control. Additionally, the intense radiation in the reactor core meant that the pressure vessel, uranium fuel rods, and a multitude of pumps, pipes, and valves had to be made of more expensive, higher-quality materials than those used in fossil power plants. The coolant also had to be extremely pure.

Furthermore, a nuclear power plant could not be completely "turned off," a feature unique to the nuclear industry. Due to the unstoppable process of radioactive decay, a reactor continued to produce large amounts of heat after being shut down. The implication was that cooling and safety systems had to be exceptionally reliable; they had to continue operating at all times, including during earthquakes, floods, and military attacks. Failure to ensure this would result in the reactor overheating and potentially melting down, which could lead to widespread radioactive contamination.

Optimistic nuclear engineers believed they could cope with these challenges. However, from the 1950s to the 1970s, there was a great deal of trouble at the nuclear power plants that were taken into operation. Engineers struggled to repair pipe breaks and correct pump and valve failures and to understand why their emergency systems did not work as planned. Then came the big accidents: Three Mile Island, Chernobyl, and Fukushima.

All of this damaged the public image of nuclear energy. Accidents and near-accidents broke the *nuclear social contract*: the public's willingness to accept nuclear energy in return for the promise that it would not cause serious harm. Governments and regulatory agencies grew increasingly wary of the nuclear industry. The industry was forced to install additional control technologies and safety systems at their facilities. While these made nuclear energy safer, they also made it increasingly complex and expensive. I

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conceptualize this phenomenon as a *cost-complexity trap*: a path-dependent process in which discovering new risks and producing technical fixes to address them generated a trajectory of growing technological complexity, rising capital expenditures, and financial losses.

At the meso level, nuclear builders had to find ways to integrate their plants into local and regional environments. This resulted in intriguing new *envirotechnical systems*, to use a concept proposed by Sara Pritchard.[34] The most critical challenge was tapping into natural water flows, needed for nuclear cooling. Immense volumes of cooling water were needed. A standard 1,000-megawatt (MW) reactor consumed around 50 cubic meters (13,000 gallons) of water *per second*, corresponding to a mid-sized river or a large irrigation canal. While fresh nuclear fuel arrived at a nuclear plant once every year or so, cooling water needed to be supplied continuously. Any disruption in the flow could lead to the reactor overheating and, in the worst case, a core meltdown. Therefore, large-scale plants had to be built at sites where large volumes of water could be reliably extracted. Only in this manner could the immense power of nuclear fission be harnessed. Micro-engineering at the level of atoms and nuclei was made possible through mesolevel engineering of wet landscapes. Seas, lakes, and rivers became an integral part of the world's nuclear facilities—much like a river, as the philosopher Martin Heidegger once asserted, was always part of the hydro-power plants built within it.

This *wet nuclear extractivism* required that nuclear engineering merge with older, seemingly mundane hydraulic practices. For example, nuclear builders engaged in large-scale dredging and rectification of rivers. They constructed canals, pools, locks, dams, and weirs, with the aim to ensure a constant supply of cooling water—fifty cubic meters per second for each reactor. Worthy heirs of ancient hydraulic civilizations, they built water storage reservoirs in the form of ponds and artificial lakes. Levees, dikes, and seawalls, designed to protect the plants from flooding, added to the technological ensemble.

This hybridization of (new) nuclear and (old) hydraulic engineering practices, and the resulting envirotechnical entanglements, generated a set of problems separate from those inside the nuclear plant itself. The "wet" siting of nuclear power plants near rivers and lakes raised concerns about the potential contamination of drinking water with radioactivity. At numerous sites nuclear operators found themselves competing with

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agriculture and nonnuclear industries for scarce water resources. And then there was the problem of "thermal pollution" of natural waterways resulting from the large quantities of warmed cooling water discharged back into them.

Nuclear builders sought to address these issues through technical fixes such as cooling towers. However, these altered the appearance of entire landscapes in a way that was anything but popular. They also gave rise to fears of a changed regional climate due to the continuous ejection of water vapor from the towers. Farmers, in particular, were worried. These concerns marked the beginning of a more critical stance toward nuclear power among aquatic scientists, water agencies, and the general public, setting the tone and forming a stepping stone for what would become powerful antinuclear movements. Therefore, understanding wet nuclear extractivism is essential to understanding the historical evolution of public opposition to nuclear energy. Today concerns over thermal pollution of rivers and lakes continue to be debated in the Western world in connection with climate change and rising water temperatures, and they are at the heart of the political and public debates over nuclear energy in China and India.

One possible solution to the challenges posed by riverine nuclear projects was to build nuclear power plants near the coast. However, the nuclear builders faced different threats there, as the plants turned out to be vulnerable to storms, hurricanes, and tsunamis. In March 2011, a massive tsunami destroyed the Fukushima Daiichi nuclear power plant (NPP) in Japan. Several countries abruptly abandoned nuclear energy after this event because they now definitely viewed it as too dangerous. In line with the cost-complexity trap, the Fukushima accident also generated demands for new, expensive safety systems, in Japan and internationally. Faced with such costs, some nuclear operators chose to prematurely close their plants.

At the macro level, the analysis targets the nuclear fuel cycle. The focus shifts from wet to dry extractivism and visions of a nuclear circular economy. In fact, "fuel" is misnomer when it comes to nuclear energy because there is no fire in a nuclear power plant. Nothing burns. Rather, heat is produced through nuclear reactions involving uranium, a heavy metal. Like other metals, uranium must be extracted through mining, and the deposits must be identified through geological prospecting and exploration. The ore must then be purified and converted into a suitable chemical form, similar to the historical processing of iron, zinc, or bauxite. Moreover, the uranium

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had to be enriched, except in a few plants, such as those operating in the United Kingdom and Canada, which ran on "natural" uranium.

Inspired by the historical tradition of resource colonialism—with roots in the Bronze Age tin trade and later incarnations in colonial extraction of gold, silver, rubber, timber, and oil—the nuclear industry set out to ensure control of suitable uranium deposits. A functional supply chain was built up for turning colonial uranium—extracted in regions like the American West, First Nation Canadian territories, Soviet Kazakhstan, Aboriginal Australian sites, and postcolonial Niger in former French West Africa—into nuclear fuel. Yet the harsh conditions under which the uranium miners worked and the immense environmental and health problems that accompanied dry nuclear extractivism gave rise to conflict, both in the mining nations themselves and in the countries whose nuclear plants used the radioactive metal.

Managing spent nuclear fuel became an even more contentious challenge. In the early days of atomic energy, it was assumed that all spent fuel would be "reprocessed." Valuable plutonium would be separated out, sold, and reused. Along with the "depleted" uranium, the plutonium would be used in advanced "breeder reactors." Highly radioactive fission products such as cesium and strontium, for their parts, would find industrial applications. This grand vision of a *nuclear circular economy* was conceptually based on nineteenth-century ideals for recycling agricultural resources and the impressive tradition in the modern chemical industry of reusing virtually all waste products.[35]

Yet, the efforts to hybridize (new) nuclear engineering with (old) circular economy practices were fraught with conflict. As it turned out, recycling spent nuclear fuel was something entirely different from recycling nonnuclear substances such as nitrogen, methane, or zinc, because the material emitted significant amounts of decay heat and was intensely radioactive. The engineers encountered nearly insurmountable practical problems when developing a reprocessing complex. They tried out radiochemical methods that turned out to be unexpectedly costly, environmentally hazardous, and difficult to control safely. And then there was the fear that the envisioned "plutonium economy" could lead to uncontrolled nuclear weapon proliferation.

Starting in the late 1970s, more and more countries with nuclear reactors opted to give up their reprocessing ambitions. This created a dilemma at

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the nuclear power plants, because there was no obvious alternative method of getting rid of the spent fuel. No one knew what to do with this exceptionally dangerous material. As a result, the elegant vision of a nuclear circular economy morphed into what was increasingly perceived as an Achilles heel of nuclear energy. The waste crisis boosted an already strong antinuclear movement. Some countries concluded that the problems with spent nuclear fuel and radioactive waste were so serious that they decided to abandon nuclear energy and invest in other energy sources.

In this way, an in-depth analysis of nuclear energy's global history at three different levels allows us to understand why nuclear power failed to become a dominant technology for electricity production—in spite of its highly attractive underlying idea, vastly superior fuel density, and lack of traditional pollutants. The implicit argument is that we cannot explain nuclear energy's failure by examining the history of nuclear reactor development, nuclear accidents, or antinuclear mobilization in isolation. Instead, we must zoom out and examine how actors struggled to integrate nuclear energy with the "conventional" parts of nuclear power plants, with wet landscapes, and with circular economy ideas.

Energy Transitions as the Craft of Combination

The book's broader implication concerns the nature of energy transitions. The failure to turn nuclear energy into a dominant energy source showcases how energy transitions can go wrong. Attempted transitions can end in failure and cause great harm, despite initial sociotechnical promises and expectations that seem fully reasonable. From this point of view the global history of nuclear energy should be regarded as a cautionary tale in debates about past and present attempts to introduce new energy technologies.

Atomic Disenchantment suggests that energy transitions, whether failed or successful, are best understood as attempts to hybridize "old" and "new" technologies, "complex" and "simple" systems, and "high-tech" and "low-tech." Success hinges on whether actors can master this craft of combination. Scholars such as Jean-Baptiste Fressoz have noted how new energy sources rarely replace old ones. Rather, the dominant pattern is one in which new categories of fuels and technologies are added to an already existing "mix," a point that can easily be demonstrated with simple statistical figures.[36] The case of nuclear energy calls for an additional layer in

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the analysis. New energy sources don't necessarily replace old ones; nor do they simply appear side by side with older ones. Instead, they actively tie into and connect with what is already there. Historically, nuclear reactors built on and forged connections with existing fossil fuel technologies as well as with extractivist traditions, both wet and dry. Today we see how wind energy and electric vehicles, in a similar fashion, tie into existing turbine and engine technologies as well as into well-established resource chains and mining practices. Scholars have observed that even solar energy "is reproducing major spatial and ownership logics of fossil fuels, albeit with political economic discontinuities in the nature of investments and subsidies."[37]

If viewed through the lens of Schumpeterian innovation theory, there is nothing surprising about this. It's only natural for tomorrow's technologies to evolve from today's. Yet this thinking has so far not been properly incorporated into mainstream analyses of energy transitions. Furthermore, the literature has neglected to address how attempts to combine the old with the new generate unforeseen dangers and risks. A new energy source or technology is rarely risky or dangerous in and of itself; rather, it is the integration of new innovations with old components, systems, and traditions that makes them vulnerable.

Overview of Ensuing Chapters

The book is divided into two parts. Part I examines nuclear science's three marriages with older technological traditions and practices as discussed above. Chapter 1 zooms in on the micro level to trace the invention and early evolution of the "nuclear steam engine." The chapter follows the rise of political expectations for nuclear power, the engineering efforts to hybridize military nuclear experiences with older steam technologies, and the technical and economic challenges resulting from these experiments. Key topics include the competition between nuclear power and a rapidly progressing fossil fuel industry, the emergence of an early safety discourse, and the question of scale in nuclear engineering.

Chapter 2 shifts the focus to the meso level. It elaborates on nuclear energy's envirotechnical entanglements and the attempts to merge nuclear science with classical hydraulic engineering practices. The chapter zooms in on the hydraulic arrangements at specific nuclear sites, noting that each

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nuclear power plant ties into its surrounding landscape in a strongly idiosyncratic way. The chapter then discusses the conflicts around thermal pollution, a phenomenon that was identified as the most pressing dilemma at riverine nuclear sites, as well as the rise of cooling towers as a technical fix. Lastly, the chapter addresses the challenge of constructing coastal nuclear power plants, which faced risks of a different kind.

Chapter 3 turns to the macro level of worldwide nuclear development and, more specifically, the pursuit of integrating nuclear engineering with traditional resource extraction and recycling practices. The chapter analyzes the different stages of the "nuclear fuel cycle," beginning with uranium mining and its historical links to nonnuclear extractive enterprises. Uranium enrichment, the nuclear equivalent of oil refining, is discussed against the backdrop of nuclear weapon proliferation fears. The chapter then turns to the centerpiece of the nuclear circular economy—the reprocessing of spent nuclear fuel—and to the global dilemma of radioactive waste management.

Part II examines the sociotechnical pathways leading to the stagnation and decline of nuclear power. Chapter 4 elaborates on the grand nuclear visions that many countries formulated around 1970. Almost everywhere, it was taken for granted that nuclear power would become a dominant energy source. However, the ambitious expansion plans were increasingly questioned as the nuclear builders ran into obstacles. Mesolevel challenges sparked early opposition to nuclear power, followed by microlevel concerns about reactor safety. Finally, macrolevel fuel cycle worries emerged in a significant way, albeit in different forms in different parts of the world.

Chapter 5 reconstructs the stagnation of nuclear power in different national contexts. Most national programs were scaled back significantly from the mid-1970s onward, and some were abandoned. Clashes and controversies related to the three analytical levels discussed in the first part of the book explain this negative development. However, the pathways to decline differed greatly from country to country. Only a few countries, notably France, succeeded in making nuclear power a dominant energy source. Nuclear energy's share of global electricity supply peaked at 17 percent in 1996, after which it began to decline.

Chapter 6 addresses the pursuit of a "nuclear renaissance" in the twenty-first century. It elaborates on the nuclear industry's hopes to turn stagnation

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into renewed growth, based on new reactor models and supported by political ambitions to decarbonize national energy systems and strengthen energy security amid growing geopolitical turbulence. The renaissance was, first and foremost, a discursive phenomenon. Materially, the first quarter of the new millennium saw a continued decline of nuclear energy worldwide, except for modest nuclear investments in a few Asian countries. Similar to the global stagnation discussed in the previous chapter, I argue that the failure of the nuclear renaissance can be explained by a combination of micro-, meso-, and macrolevel factors. These factors range from the Fukushima accident as a mesolevel "envirotechnical disaster" to the microlevel cost-complexity trap and the macrolevel paralysis of efforts to manage spent nuclear fuel worldwide.

The epilogue discusses the present-day situation and how the global history of nuclear power can inform the debate about the future. It emphasizes the paradoxical coexistence of unprecedented enthusiasm for nuclear power in the 2020s with its continued marginalization in the global energy system. The chapter concludes with a future outlook for nuclear power in an era of renewables and the risk of future nuclear disasters.

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I Forging the Global Atom: Nuclear Science and Its Three Troubled Marriages

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1 Inventing the Nuclear Steam Engine

In August 1945 the United States dropped two atomic bombs on the Japanese cities of Hiroshima and Nagasaki, violently demonstrating "the miraculous powers of atomic-fission energy."[1] In less than three years, the scientists and engineers working for the Manhattan Project had managed to turn nuclear fission—a phenomenon discovered by European scientists before the war—into the most lethal and powerful weapon the world had ever seen.[2]

There were hopes early on that this military feat would spill over into a realm of peace. Optimists proclaimed that atomic energy and the "plutonium economy" would revolutionize everything from air travel and civil engineering to food and water supplies.[3] David Lilienthal, the first chairman of the US Atomic Energy Commission, pointed to the "almost limitless beneficial applications of nuclear energy," while Manhattan Project physicist George Gamow argued that "the newly discovered possibility of liberating the hidden energy of uranium atoms promises us an almost unbelievable technical progress in the years to come." Winston Churchill believed that "the exploitation of nuclear energy may come to be regarded as the most important step taken by man in the mastery of nature since the discovery of fire." In particular, nuclear engineering would pave the way for a new kind of power plant, which would generate electricity in a manner that was far cheaper, more environmentally friendly, and less cumbersome than coal power plants, which had dominated the global electricity mix until then. Heat, light, and power from such plants would "be so cheap that their cost can hardly be reckoned," to quote one early visionary.[4]

Yet the road from atomic bombs to nuclear power plants turned out to be long and bumpy. A quarter of a century after Hiroshima and Nagasaki,

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nuclear energy still contributed only negligibly to global electricity generation, and it still appeared uncertain whether it would ever become cheap enough to rival fossil fuels. This was a disappointing outcome for those who, in the aftermath of the Manhattan Project, had envisioned the rapid rise of nuclear energy to prominence.

Seeking to explain why civil nuclear power was so slow in coming, this chapter takes a step back from the popular idea of atomic energy as a science-based technology. Although it is tempting to view a nuclear power plant as a mere extension of scientific advances in nuclear physics and chemistry, I argue that it is more helpful to view it as a "new combination," in the Schumpeterian sense, of already existing technologies. The Manhattan Project had produced a set of key innovations, including uranium enrichment plants and plutonium-producing nuclear reactors, which did rely heavily on advances in science and which became useful stepping stones for civilian developments. Yet these bomb-making machines lacked many of the key components and subsystems that would be essential in nuclear power plants, such as pressure vessels, heat exchange systems, steam turbines, and electric generators. These would have to be brought in from a very different technological tradition: that of coal power plant and steam engine construction, with deep roots in the eighteenth-century Industrial Revolution.

The First Steps

Almost every industrialized country set up committees to study nuclear fission in the aftermath of Hiroshima and Nagasaki, and many established state-funded research programs to further explore the phenomenon. The atom attracted the attention of a wide range of actors, both military and civilian. On the military side, not only the world's armies, but its navies and air forces became interested. Civilian stakeholders included electrical utilities, chemical and heavy industries, physicians and medical experts, transportation engineers, and natural scientists who viewed nuclear reactors as new research tools.[5]

The extent to which civilian applications were of interest varied from country to country. The Soviet Union, Britain, and France decided early on to acquire nuclear weapons of their own, at whatever cost. For these countries, civilian applications were of secondary importance. Germany, Italy, and

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Japan, by contrast, were initially prohibited from engaging in nuclear research. When they were finally permitted to do so, the focus was ostensibly on civilian applications only. The smaller industrialized nations were, in theory, free to determine their own pathway into the atomic age. Yet they soon became painfully aware that they lacked the scientific, technological, and financial capacity to do everything. Most of them opted to proceed carefully, awaiting developments in the larger countries while trying to keep all options open.[6]

Those who had the technical and financial muscles built research reactors. The United States started up its first "pile" (as the early reactors were called) in December 1942 as part of the Manhattan Project. Canada, which had set up a nuclear research laboratory nearly as early, became the second country to launch a reactor; it went "critical" (that is, reached a self-sustaining nuclear chain reaction) only weeks after Hiroshima and Nagasaki. A year later the Soviet Union started up its F-1 reactor in Moscow under the guidance of Igor Kurchatov. In August 1947, Britain began operating Western Europe's first pile at Harwell, near Oxford. France followed suit with its Zoé reactor, which began splitting atoms in the outskirts of Paris in December 1948.[7]

Among the smaller nations, Sweden was the early mover, initiating construction of its R1 reactor in a cavern twenty-five meters below central Stockholm in 1951.[8] Other small countries found it too challenging to build reactors of their own at such an early stage. They had to wait until after 1954, when the United States, Britain, and Canada relaxed their secrecy policies and began forging friendly nuclear ties with a range of countries in both Europe and the Global South.[9] The Soviet Union launched a similar atomic friendship program in the communist world. In this way, the number of countries with research reactors grew rapidly around 1960 on both sides of the Iron Curtain.[10]

The research reactors allowed scientists and engineers to explore the fundamentals of nuclear fission. They learned about uranium in various forms, about plutonium, and about radiation. They experimented with different fuel configurations and tried out materials such as graphite and heavy water as "moderators," which were needed to keep the nuclear chain reaction going. But the research reactors were not nuclear power plants. They did not involve the generation of electricity. Achieving that would require experiments on a different scale and the involvement of actors from an older engineering culture.

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The US National Reactor Testing Station

In December 1946 the United States set up the Atomic Energy Commission (AEC). The Commission took over most of the activities that had previously fallen under the Manhattan Project. Its primary function was to continue developing nuclear weapons, but a secondary task was to explore nonviolent applications of nuclear fission.[11] This entailed, in particular, the development of electricity-generating nuclear power plants and naval nuclear reactors for propulsion. By late 1948 the AEC had developed a research plan covering a wide spectrum of reactor types that could conceivably be deployed for these purposes. Scientists at the AEC's Oak Ridge and Argonne laboratories spearheaded this effort, which progressed further in the following years. Over time, the light-water reactor in two forms—the pressurized water reactor (PWR) and the boiling water reactor (BWR)—and the fast breeder reactor crystallized as the most promising civilian reactor models. The US laboratories were less interested in gas-graphite and heavy-water reactors, two alternatives that inspired nuclear programs elsewhere in the world (see the nuclear energy glossary at the end of the book).

In order to produce electricity, however, the reactors needed to be linked to an electric generator. The AEC's scientists looked to coal power plants for inspiration. These plants used boilers to heat pipes through which water circulated. The resulting steam was fed into a turbine, causing it to spin. By connecting the steam turbine to a generator, the coal engineers were able to extract the turbine's rotational energy to produce electricity. The scientists reasoned that a similar arrangement could be used to harness nuclear fission. They merely needed to replace the fossil boiler with a nuclear reactor. The rest of the power plant, or so it seemed, could remain largely unchanged.[12]

To try it out, the AEC sought the cooperation of the fossil-industrial complex. Three groups of companies were of particular interest in this context. The first group specialized in building steam turbines and electric generators. This was an oligopolistic business dominated by two firms, General Electric and Westinghouse. The second focused on boiler technology and formed another oligopoly, led by Babcock & Wilcox and Combustion Engineering. The third group consisted of the nation's major engineering and construction firms, the most significant of which was the Bechtel Corporation. All three groups welcomed the AEC's interest, eyeing a unique

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opportunity to establish themselves as key players in what many analysts thought would become a massive industry.[13]

Cooperation between the AEC and the fossil companies took off in earnest in 1949, when the Commission launched the National Reactor Testing Station in Idaho. The aim was to test the new reactor types that were being invented but also to promote the merger of nuclear science and steam engineering. Here, for the first time, nuclear-oriented scientists and engineers were able to engage not only with uranium, moderators, coolants, and control rods but also with pressure vessels, water pumps, heat exchange systems, steam turbines, and electric generators. In particular, actors were able to explore, on an experimental scale, nuclear power plants as complex systems, learning about the interaction between a multitude of components and subsystems. Some of these originated in nuclear research, while others had been developed in the context of steam engine and coal power plant construction and operation.[14]

The most notable projects in Idaho included a submarine reactor for the Navy, a series of early boiling water reactors summarized under the acronym BORAX, and an experimental breeder reactor (EBR). For the Navy's reactor, project leader Hyman Rickover selected Westinghouse as his primary partner, inviting their engineers to refine the nuclear scientists' preliminary design of a pressurized water reactor. The boiling water experiments attracted the attention of General Electric, which, since 1946, was also in charge of the AEC's plutonium-producing reactors. For the EBR project, scientists from the Commission's Argonne Laboratory collaborated with Bechtel.[15]

The EBR facility was the first to be completed, in August 1951. Four months later the reactor was connected to a small steam turbine. The turbine-generator set powered four light bulbs and subsequently provided enough electricity (around 200 kW) to light up the reactor building and power the reactor's coolant pumps. In July 1955 this historical feat was followed up with the connection of one of the BORAX reactors to a 2-megawatt (MW) steam turbine. This made it possible to light up the nearby town of Arco with nuclear electricity "for more than one hour."[16] In the meantime, the Navy's reactor went critical in March 1953. Two months later it produced steam that turned a propeller. This enabled the US Navy to launch the world's first nuclear-powered submarine, the *Nautilus*, in 1954.[17]

The Idaho projects were not unequivocally successful, however. A bad omen for the future of fast breeder reactors came in November 1955, when

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EBR-I suffered a partial core meltdown—the first in what would turn out to be a long series of breeder accidents worldwide. The BORAX reactors also experienced meltdowns, resulting from experiments that pushed the reactors to their limits.[18] In the case of Rickover's submarine reactor, a longer test run in June 1953 exposed multiple problems, as condenser tubes and steam generators sprung several leaks and the water level unexpectedly dropped due to control failures. Rickover concluded that more attention would need to be given to seemingly mundane engineering tasks to ensure the reactor's safe operation. Deriding the nuclear scientists' excessive focus on theoretical aspects, he argued that plant design consisted of "95% engineering and 5% nuclear physics." Building a nuclear power plant was, in Rickover's view, "mostly an exercise in plumbing."[19]

America's First Nuclear Power Plants

The US electricity industry did not participate in the Idaho experiments, but many utilities took a keen interest in them. Electricity demand was growing at a breakneck pace, roughly doubling every decade, so the utilities were busy building ever more and ever bigger power plants, most of which ran on coal. They were very interested in new energy sources that could supplement coal as the resource base.[20] Atomic energy seemed like an interesting option. They faced considerable hurdles, however, when seeking to learn more about the new technology. Strict legislation, which defined atomic energy as a mainly military technology, made it difficult for civilian actors to keep abreast with nuclear technological progress. The AEC was aware of this and did its best to create a forum where the utilities' engineers and the commission's nuclear scientists could interact. In 1947, it established the Industrial Advisory Group, which would be allowed to "survey classified agency activities for commercial possibilities." Four years later this cooperation was expanded through the Industrial Participation Program, which encouraged the utilities and other private actors to submit proposals for reactor projects.[21]

The congressional Joint Committee on Atomic Energy became another ardent supporter of relaxing secrecy. In summer 1953 it organized a series of public hearings to discuss the shift to private development of atomic energy. Around the same time, the AEC decided to construct the Shippingport atomic power station, America's first reactor designed solely to generate

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electricity. It was a scaled-up version of Rickover's naval reactor, which was considered the most successful project thus far. Westinghouse, the designer of that reactor, was commissioned to build it. Babcock & Wilcox and Foster Wheeler were selected to manufacture the steam generators. The Duquesne Light Company, a local utility, would operate the plant. There was only one problem with that division of labor: The 1946 Atomic Energy Act prohibited private ownership of atomic reactors. As a result, an unusual ownership structure emerged: The AEC would own the "nuclear" part, and Duquesne would own the "steam" part of the Shippingport station. Duquesne would pay the AEC for the steam generated through nuclear fission and use it to produce electricity, feeding it into its electrical grid.[22]

The growing political enthusiasm for civilian nuclear energy that became apparent in 1953 culminated in President Eisenhower's "Atoms for Peace" speech at the UN General Assembly that December. A few months later, in August 1954, Congress passed an updated Atomic Energy Act that officially permitted and encouraged private involvement in developing atomic energy for peaceful purposes. The new legislation stimulated interaction between the AEC, the equipment suppliers, and the electric utilities. It seemed as if the stage was set for commercialization of the atom. The AEC, eager to "advance the time when nuclear power will become economically competitive," pushed this development by launching a Power Demonstration Reactor Program (PDRP), which allowed private companies to access AEC funds for "a portion of the expense of reactor plants."[23]

A group of fifteen enthusiastic utilities, most of which were privately owned, led the way in promoting America's first nuclear power plants.[24] Some were so eager to embrace nuclear power that they willingly funded the construction of nuclear projects that were essentially demonstration facilities, similar to the Idaho reactors, rather than full-scale commercial power plants. Inspired by the futurist zeitgeist of the mid-1950s, they were convinced that such facilities, which would almost certainly make a loss, would speed up the maturation of the technology in such a way that big profits could be expected later on. The utilities formed close partnerships with Westinghouse, General Electric, and Bechtel, who had gained significant nuclear expertise through their involvement in various AEC projects. They also partnered with Babcock & Wilcox and Combustion Engineering, the boiler manufacturers who were looking to expand into nuclear construction.

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Most of these early nuclear power plants (NPPs), which were constructed from 1956 onward, were small scale. Three larger projects stood out: the Indian Point, Dresden, and Yankee stations. Indian Point, the largest of the three, had a nominal capacity of 275 MW, comparable to the largest coal power plants of the era. Consolidated Edison, a regional utility, built it only thirty-five miles north of Manhattan in cooperation with Babcock & Wilcox. At Dresden, Bechtel and General Electric took the lead, convincing Commonwealth Edison of Chicago to build a 180 MW nuclear power plant forty-three miles from the Windy City. The plant featured a boiling water reactor.[25] The Yankee NPP, for its part, was part of the government-subsidized PDRP scheme. Aside from government support, it was funded by a group of New England utilities that saw nuclear energy as a suitable response "to the region's fossil fuel cost disadvantage." A smaller, but technologically daring, project was championed by Detroit Edison. It sought to commercialize the fast breeder that the AEC, in cooperation with Bechtel, had pioneered in Idaho a few years earlier. Detroit's controversial president, Walker Cisler, known as a champion of private enterprise, insisted on the project to prevent the AEC from playing a leading role in civilian breeder development.[26] The Dresden and Yankee stations along with Detroit's breeder were all brought online in 1960. Indian Point followed in 1962.

The Rise of the First Safety Concerns

The utilities pursued these early nuclear projects with enthusiasm. But one thing worried them: What would happen in the event of an accident? With decades of experience of operating coal power plants, the utilities knew all too well that many things could go wrong in such plants. Their worst nightmare was a boiler explosion, a dramatic phenomenon that regularly caused accidents in thermal power plants as well as in factories, locomotives, and steamships. There had been "thousands of boiler explosions and thousands of deaths" in the age of steam.[27] Most of these accidents were caused by issues with the cooling system or material decay. Valves often got stuck, pumps stopped working, and pipes ruptured and leaked. If civilian nuclear plants were to be modeled after coal power plants, it seemed all too obvious that such problems would plague nuclear power plants, too. The American Society for Mechanical Engineers (ASME) shared this interpretation, concluding that a nuclear reactor should undergo the same licensing

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procedure and adhere to the same ASME standards—specifically, the influential Boiler and Pressure Vessel Code—as traditional coal boilers.[28]

Upon closer inspection it appeared that hybridizing nuclear and steam technologies might result in power plants that were even more dangerous than coal power plants. One reason was that the energy density in a nuclear pressure vessel was a hundred times or so greater than that in a coal boiler of the same size. This made controlling the heat transfer much more challenging. Furthermore, reactor vendors realized early on that the materials composing the key components of a reactor would need to be of a higher quality than those of a coal-fired station. This was due to the potentially destructive effects of radiation. To prevent destructive corrosion and embrittlement, the reactor pressure vessel and all the pipes and pumps in the primary cooling circuit had to be made of special, expensive types of steel. When it came to the cladding of the fuel rods, no steel was good enough. Engineers struggled to find a material that could withstand the intense radiation. Aluminum was used in a few early plants but was soon deemed unsuitable. Ultimately, the vendors settled on zirconium, a rare and expensive metal that was extracted in only a few places worldwide.[29]

Another notable difference from coal was that a nuclear power plant could not easily be "turned off." Due to unstoppable decay heat—which accounted for about 7 percent of a reactor's total heat production—heat and steam continued to be generated long after the plant had been shut down. This meant that, unlike coal power plants, nuclear power plants had to be equipped with heat transfer systems that guaranteed the fuel would be properly cooled in all conceivable situations.[30] Otherwise, the accumulation of residual decay heat could lead to a core meltdown. The main nightmare scenarios were a major pipe rupture jeopardizing the reactor's cooling system and an electricity blackout bringing the cooling water pumps to a halt. In recognition of these risks, reactor designers proposed building emergency cooling systems, consisting of separate sets of pumps and pipes designed to come to the rescue in the event of a major pipe break or pump failure. To reduce the risk of a station blackout, they also emphasized the need for "three independent primary power sources," typically two independent high-voltage transmission lines plus diesel generators as a backup source.[31]

The risk of failure was of particular concern because a nuclear accident could lead to the spread of radioactivity over a large area. If accidents

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were to be expected from time to time, as in fossil-fueled stations, then special measures clearly had to be taken to protect the general public from radioactive exposure—especially if nuclear plants were to be built in or near densely populated areas. In response, the AEC required utilities to invest in specially designed "containment" buildings, made of steel and concrete, as an outer safety barrier.[32] These artifacts, which in the early years of civilian nuclear power were often spherical in shape (figure 1.1), became visual icons of the emerging civilian nuclear era. Their defensive character conveyed a sense of unusual risk. If a nuclear power plant was "just another steam engine," or so it seemed, it was one of a uniquely dangerous kind.

Although they did not spark any public debate at the time, the safety issues were discussed internationally at events such as the Geneva conferences on the peaceful uses of atomic energy. Scientists and engineers also analyzed reactor risks in *Nuclear Safety*, a specialized journal that the AEC began publishing in 1959.

In the meantime, Rickover's Shippingport atomic power station went critical for the first time in December 1957. Its first year was troubled: There were recurring pump failures, steam generator leaks, and malfunctioning valves in the cooling system. The result was an array of operating incidents. Although performance improved over time, Rickover remained frustrated. He expressed his concerns about allowing nonmilitary personnel to oversee nuclear power plants. The lack of military discipline, he reasoned, would increase the risk of serious accidents. The "whole reactor game," he explained, "hangs on a much more slender thread than most people are aware. There are a lot of things that can go wrong and it requires eternal vigilance."[33]

Another problem was that Shippingport produced expensive electricity. According to some comparisons, the price per kilowatt-hour was around ten times that of coal-generated electricity.[34] The situation was much the same with subsequent plants. For example, the Indian Point NPP was projected to cost $55 million, but the actual cost was over twice that, at $127 million.[35] In other words, the prospect of commercially competitive nuclear energy did not look rosy. Would nuclear energy ever be able to compete? That appeared highly uncertain. There was no end in sight to the technical challenges that utilities and reactor vendors encountered in their quest to merge nuclear science with steam engineering. The need for

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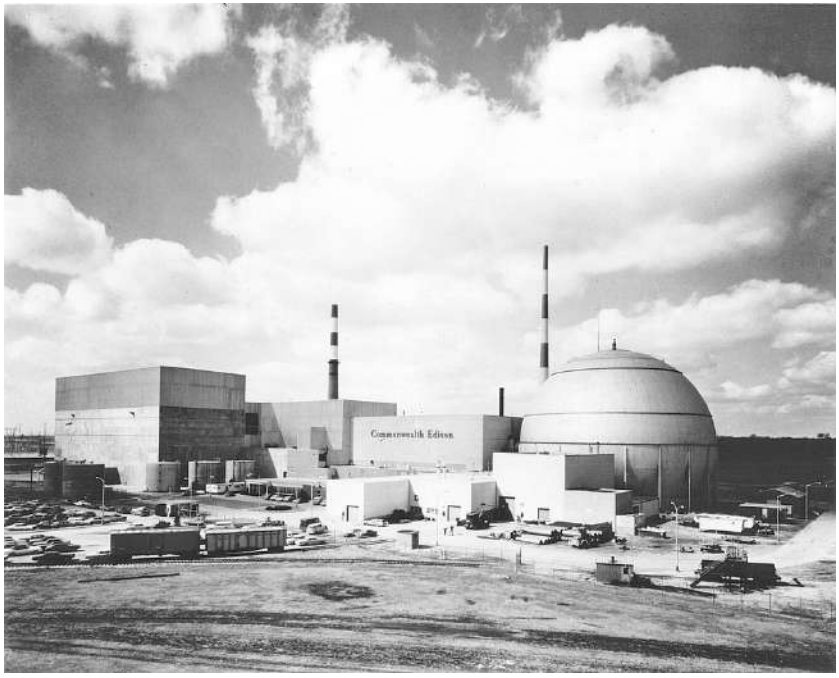

Figure 1.1
The Dresden nuclear power plant with its spherical containment building. *Source*: Wikimedia Commons.

robust and reliable control systems, advanced and exotic materials that could withstand the intense radiation, airtight containment buildings, and flawless pumps, pipes, and valves were just a few of the challenges that led to escalating costs and construction delays. After a brief period of nuclear euphoria in the years around 1955, the US nuclear industry found itself in a "deep disillusionment" and "an open crisis," according to a 1958 German report.[36] Four years later *Science* magazine observed that "the glamour has gone out of atomic power." Ex-AEC chairman David Lilienthal judged that the US atomic power program "has been quite a flop, and is not to be taken seriously."[37] Between 1956 and 1963, sixteen nuclear reactors designed to produce electricity began construction in the United States, but none of them managed to make nuclear energy commercially attractive.[38] All in all, it seemed as if the intriguing new technology of nuclear power might face an unhappy, premature end.

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The Soviet Union's Nuclear Samovars

Two countries moved faster than the United States in launching their first electricity-generating nuclear plants: the Soviet Union and Great Britain. Eager to catch up with the United States in the military realm, both nations built plutonium-producing reactors early on. After detonating their first atomic bombs in 1949 and 1952, respectively, they set out to apply that experience to civilian purposes.

Nikolai Dollezhal, a skilled engineer who had designed the Soviet Union's plutonium reactors, oversaw the construction of the country's first civilian nuclear plant. Built at Obninsk, 110 km southwest of Moscow, this machine combined military reactor technology with what looked like a normal coal power plant, comprising a steam turbine, an electric generator, and a multitude of pipes, pumps, and valves. It was a small-scale facility designed to produce no more than 5 MW of electricity, "barely enough to power a locomotive." But unlike Idaho's EBR reactor, which produced a miniscule 0.2 MW, its sole purpose was to demonstrate the feasibility of nuclear electricity generation.[39]

Steam engineers were called in to figure out how best to integrate the fossil components of the plant with the nuclear machinery.[40] Some of the fossil equipment was secondhand. For instance, a new steam turbine did not need to be manufactured because an old 5 MW turbine built by the German company MAN before World War I was available. It had originally been intended for use in a Russian coal power plant. Thus, a historical artifact from the fossil fuel industry became a key component of "the world's first nuclear power plant," as the Soviets proudly called it.[41]

The Obninsk NPP was commissioned in June 1954, though not without problems. There were leaks in several cooling water pipes, as well as all sorts of false alarms and control system issues. Then, engineers found oxygen in the core and feared a disastrous steam explosion. Dollezhal proposed closing the reactor prematurely, but Efim Slavsky, his superior at the Ministry of Medium Machine Building (Sredmash), emphasized the pioneering plant's great symbolic value. He insisted on keeping the station in operation after extensive repairs and retrofitting.[42]

In summer 1955 the Kremlin approved Sredmash's proposal to develop no less than four types of large-scale nuclear power plants: (1) a graphite-moderated, light-water-cooled reactor based on the Obninsk experience,

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(2) a pressurized light-water reactor drawing on experiments with a naval reactor, (3) a heavy-water-moderated, gas-cooled reactor, and (4) a graphite-moderated, gas-cooled reactor. Each plant was expected to produce around 100–200 MW of electricity. The Twentieth Congress of the Communist Party, held in 1956, specified that at least 2,000 MW of civilian nuclear capacity should be operational by 1960.[43]

In order to achieve this, the Soviets had to combine their nuclear-scientific expertise with available steam engineering competencies. This resulted in cultural clashes. The scientists, who were totally focused on the nuclear systems and components, considered the steam portion of a nuclear plant to be an unexciting, old-fashioned "tail" (*khvost*) of the reactor. Having built the first Soviet atomic weapons, they were confident in their ability to transfer their nuclear expertise to the civilian sector. The steam engineers complained that precisely this high self-esteem "disturbed the search for correct solutions." In the eyes of the steam experts, the nuclear-scientific community had no clear understanding of the harsh realities of large-scale electricity production. The steam experts also claimed that the scientists were unaware of the economic aspects of civilian construction, because they were "used to accomplishing their tasks at any cost."[44]

Overall, the Soviets, just like the Americans, tended to underestimate the difficulty of merging nuclear science with steam engineering. After all, a nuclear power plant was not "merely a somewhat complicated samovar," as the more optimistic of the Soviet scientists joked.[45] For example, the extraordinarily high levels of energy output of nuclear fuels, compared to fossil fuels, forced engineers to devise new solutions for managing extreme heat flows. They also needed to develop new types of high-pressure circulation pumps and more powerful steam turbines. The Soviets found these tasks to be overwhelming.[46]

Consequently, the Soviet Union struggled to meet its ambitious planning targets for the 1956–1960 period. As of February 1957, none of the four planned pilot plants had begun construction. Sredmash complained about the "difficult situation," blaming the electricity industry for "not being ready to fulfill the tasks assigned to it."[47] There were delays and escalating costs. In August 1959, the Council of Ministers decided to scale back the most important project, the Novovoronezh NPP, by abandoning one of two planned reactors. The original budget for the plant's two reactor blocs was ultimately barely enough to finance one.[48]

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The Kremlin's goal of achieving 2,000 megawatts (MW) of installed nuclear capacity, as specified in the 1956–1960 five-year plan, would not be reached until the mid-1970s. The Soviets had taken an early lead by completing the Obninsk NPP. However, that reactor remained the only civilian one in operation for the time being.

Britain's Rush for Peaceful Nuclear Power

Britain, for its part, was in a hurry to increase its electricity generation capacity to meet the growing demand, but also to produce plutonium for the military's goal of building two hundred atomic bombs by 1957. In an attempt to address these challenges simultaneously, scientists and engineers at the UK Atomic Energy Authority (UKAEA) developed a reactor design capable of producing both weapons-grade plutonium and electricity for the grid. The result was the gas-graphite reactor line that established Britain as a nuclear nation. The first station of this type was commissioned at Calder Hall in 1956. It was erected next to the Windscale Piles, a pair of military reactors that produced plutonium only.[49]

For the construction of the electricity-generating portion of Calder Hall, Britain's nuclear experts turned to private companies with experience in steam engine and coal power plant construction. C.A. Parsons & Co., a company that had pioneered steam turbine manufacturing in the late nineteenth century, was the obvious choice of contractor on the equipment side, while Taylor Woodrow Construction, a prominent coal power station builder since 1945, was chosen as the main civil engineering contractor. Babcock & Wilcox, the US fossil boiler maker, made the pressure vessel.[50]

This hybridization of military nuclear projects with steam engineering laid the basis for Britain's swift entry into the civilian nuclear era. In February 1955, the government published a civilian nuclear expansion program that far surpassed those of all other Western countries in ambition. The UKAEA suggested erecting no fewer than twelve electricity-generating reactors over the next decade.[51] These reactors would be of the Magnox type, an improved version of the original gas-graphite design. The 1956–1957 Suez Crisis further emphasized the need for civil nuclear power, prompting an expansion of the program. The minister of power, Lord Mills, admitted that the capital cost of the program "would be about £770 million more than that of a comparable programme based on conventional power stations,"

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but the resulting coal savings would be considerable. Concerns that "the unit cost of electricity from the earliest nuclear power stations might prove to be slightly higher than that from conventional stations" were brushed aside, because "technical development, which might be expected to be rapid, should succeed in eliminating this excess cost."[52]

From 1956 the Central Electricity Generating Board (CEGB) and the South of Scotland Electricity Board (SSEB)—the nation's two state-run electricity monopolies—took over responsibility for building and operating the nation's nuclear plants from the UKAEA. Private industry, which would play the main role in construction, was encouraged to form consortia—each grouped around "an electrical manufacturer, a boiler manufacturer and possibly a power plant consultant"—that would then bid for different projects.[53] Construction of the first Magnox stations began in 1957. That year, work commenced on no fewer than eight reactors at four sites: Berkeley, Hunterston, Bradwell, and Hinkley Point. Over the next six years, another five plants at Trawsfynydd, Dungeness, Sizewell, Oldbury, and Wylfa began to be erected. Each plant was equipped with two reactors.[54]

The British scientists regarded their gas-graphite reactors as "inherently safe." That assessment was put to the test on October 10, 1957, when one of the two military reactors at Windscale caught fire and burned for three days. Large amounts of radioactive iodine-131 and polonium-210 were released. Since the civilian Magnox reactors were historically rooted in the military Windscale design, the disaster raised concerns about the safety of the Magnox stations. The reactor cores had to be modified, which led to delays in civilian nuclear expansion.[55]

Meanwhile, the argument that nuclear energy was urgently needed lost much of its appeal amid a mounting coal surplus and falling fossil fuel prices. Cost escalations in nuclear construction similar to those observed in the United States and the Soviet Union added to this impression.[56] Prime Minister Harold Macmillan was nevertheless of the opinion that "from the long-term point of view of our economy and our national prestige," it was "desirable that we should proceed steadily with the nuclear programme on which we have embarked." He believed that although there would be "advantages in postponing construction of further nuclear power stations until a more advanced and economic design could be produced, these are outweighed by the importance of maintaining in being the scientific and industrial staffs now engaged on these projects."[57] Similar arguments for

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nuclear expansion would subsequently be raised in other European countries, too, paving the way for numerous nuclear projects that did not actually seem rational from a technical or economic point of view.

Continental Western Europe Enters the Nuclear Age

Across the Channel, France was eager to catch up with Britain. The prospects for success were not bad, given a well-reputed French community of nuclear scientists, including Frédéric and Irène Joliot-Curie and a number of physicists and chemists who had spent the war years in North America contributing to the Manhattan Project. In addition, France had a robust fossil fuel complex that could be leveraged for the development of electricity-generating nuclear plants.

The French development was led by the Commissariat à l'énergie atomique (CEA), a state body founded in 1945. It was essentially a military agency that pursued reactor construction mainly for the purpose of weapons-grade plutonium production. A nuclear-industrial complex was established at Marcoule in southern France, where the CEA led construction of three gas-graphite reactors during the second half of the 1950s. The reactors produced respectable volumes of plutonium plus small amounts of electricity. The plutonium enabled France to successfully test its first atomic bomb in February 1960.

The "energetic" part of the Marcoule reactors was designed by engineers from Électricité de France (EDF), the nation's state-owned electricity company and its most important source of steam expertise. Its engineers were not overly happy with their role in the CEA's reactor projects, because it was all too obvious that electricity generation was not a priority. Yet they learned a great deal by interacting with the CEA's nuclear scientists.[58]

Shortly thereafter, EDF began to design its own nuclear power plant at Chinon on the Loire River. The roles of the CEA and EDF were now reversed. EDF and its steam engineers took the lead, whereby the cultural divide between the two agencies became increasingly obvious. The nuclear engineers were shocked by what they interpreted as a casual attitude from EDF, whose managers and engineers saw nuclear power as "just another way to boil water."[59] In EDF's view, however, it was imperative for nuclear builders to learn from fossil power plant construction, because it was the only feasible way to make nuclear energy profitable. The profitability aspect

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was reinforced through the adoption of a company-wide policy of *rentabilité* (economic viability), which arose from concerns in the early postwar years about cost escalation in conventional power plant construction.[60]

Chinon did not earn a good reputation. In February 1959, the first reactor at the site was still under construction when a major setback occurred: A huge crack suddenly appeared in the spherical containment building, which was designed to protect the public in case of a nuclear accident. EDF's engineers also struggled to weld the cylindrical pressure vessel of the reactor, setting the project back more than a year.[61] By spring 1963 CEA engineers complained that EDF's issues at Chinon had created "a very unfavorable impression of French nuclear technology." EDF president Pierre Massé would later admit that the utility had severely underestimated the challenge of marrying steam engineering with nuclear technology. The company had "neglected the difficulties of nuclear in every way. We underestimated the need for materials of great purity and techniques of great safety."[62]

West Germany also wished to "go nuclear," but its ambitions were initially constrained by the political situation. The Allied Control Council did not allow the occupied country to engage in reactor construction, nor in uranium extraction and processing.[63] The ban was not lifted until 1955, when the Paris Treaties made the Federal Republic a fully sovereign state. This coincided with significant international developments, including Britain's announcement of its ambitious reactor program, the organization of the first Geneva Conference on the Peaceful Uses of Atomic Energy, and the decision to create a European Atomic Energy Community (Euratom). A vivid nuclear awakening followed in Germany, leading to the establishment of a brand-new Ministry of Atomic Energy in Bonn and an ambitious nuclear research center at Karlsruhe.

Leading German physicists like Werner Heisenberg envisioned atomic energy as a distinctly science-based technology. Accordingly, they considered it natural for the scientific community to play the leading role in reactor development. Only gradually did they recognize the immense technical challenges that lay ahead, especially on the "steam side" of things. It soon became clear that the fossil fuel industry would have to contribute in a decisive way.[64]

However, the coal-oriented German electricity industry was rather skeptical. Most electric utilities thought it premature to invest in an untried

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technology such as nuclear power. And once they did decide to give the atom a try, they opted to work with reactor designs that had little in common with those favored by the scientists and the Atomic Ministry. In 1957, when RWE, the country's largest utility, decided to build Germany's first pilot-scale nuclear power plant, the 15 MW Kahl NPP, it purchased a reactor from the United States. The choice fell on an early boiling water model linked to the BORAX experiments in Idaho. This contradicted Bonn's intention to base the German nuclear energy program on domestically developed reactor types, notably heavy-water reactors and high-temperature reactors.[65]

Opinions in Germany differed about the prospects of nuclear energy smoothly hybridizing with steam technologies. Physicists such as Walther Gerlach claimed that the conversion of heat to electrical energy in nuclear reactors did not differ "in any way" from how it occurred in coal power plants. The country's first atomic minister, Siegfried Balke, jokingly commented that fossil and nuclear plants were so similar that "the inventor of the zipper" was "more ingenious than the constructor of the first nuclear power station." However, many industrial stakeholders anticipated that replacing a fossil boiler with a nuclear reactor in a steam-generating facility would not be that straightforward. They pointed to the new material problems likely to arise due to continuous, intense radiation in a reactor, among other things. In one nightmare scenario, radiation would weaken the steel in the pressure vessel until it burst, with unimaginable consequences for human health and the natural environment. RWE's president, Heinrich Mandel, believed that solutions to such problems could be worked out but that they would require costly investments. For this reason, if nuclear science were to merge with steam power, it would be essential to select the simplest reactor types possible. Only these, Mandel argued in 1959, would stand a chance of success in a commercial setting.[66]

The prospect of acquiring foreign nuclear technology meant that countries could "go nuclear" even if they lacked the capability to design reactors domestically. The US Atoms for Peace program played an important role in this context, as did the eagerness of Britain, France, and Germany to sell their reactor designs to other countries. The formation of Euratom in 1957 and, shortly afterward, the launch of a US-Euratom cooperation program, opened up further avenues for technology transfer within Western Europe and across the Atlantic.

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The importing countries were not passive recipients of nuclear technology, however. In particular, they played an active role in constructing the "conventional" part of the plants, drawing on their historical experience of fossil power plant construction. Through their coal and oil power plant projects, many utilities had forged fruitful partnerships with US equipment suppliers such as General Electric and Westinghouse long before the nuclear era. They now sought to mobilize this experience for nuclear construction.

Italy's pioneering Trino Vercellese NPP, for example, was championed by Edison, a Milan-based electric utility that in 1883 had built continental Europe's first coal power plant. During the fossil era, Edison's main foreign partner had been Westinghouse, so it was only natural that they would rely on that company's PWR reactor technology for the Trino facility, which began to be erected in 1961. Another Italian project was led by the Istituto per la Ricostruzione Industriale (IRI), a public enterprise in the electricity industry that traditionally relied on General Electric and its Italian licensees for equipment. Unsurprisingly, this led IRI to invest in a GE boiling water reactor, which began construction at Garigliano in southern Italy in 1959. Similarly, Spain built its first two nuclear power plants—the José Cabrera and Santa María de Garoña NPPs—in cooperation with American boiler and turbine manufacturers that had catered to Spanish coal power plants for decades.[67]

Sweden and Switzerland were two other West European nations that invested heavily in nuclear power. Initially, the two countries hoped to maintain independence in nuclear matters by combining their existing steam engineering expertise—represented by companies such as STAL-LAVAL and Brown Boveri & Cie. (BBC)—with substantial state investment in nuclear research and development. In Sweden, this strategy paved the way for construction of the Ågesta nuclear heat and power plant in Stockholm's southern suburbs. Becoming operational in 1964, it produced 55 MW of heat and 10 MW of electricity for urban use. Completion of the facility, which relied on heavy-water technology, was delayed by three years, and the project ended up costing five times more than originally estimated. In spite of this financial disaster, the Swedes insisted on celebrating the Ågesta plant as a national success.[68] The Swiss attempted something similar on a smaller scale, resulting in the Lucens heavy-water reactor project. It did not end happily. After only a year in operation, the reactor suffered a partial core meltdown and had to be decommissioned prematurely.[69]

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Several other West European countries hesitated about whether and, if so, when to invest in reactor projects. Although they were not insensitive to the nuclear euphoria of the mid-1950s, they noted that the more enthusiastic countries were taking considerable financial risks with a technology that might or might not become a success. So why not wait and see? Why rush into something that might not turn out well? Such considerations were omnipresent in early debates about nuclear power in countries such as Austria, Denmark, Norway, Finland, Ireland, Portugal, and Greece.[70]

Canada Goes Its Own Way

On the other side of the Atlantic, Canada had established its Chalk River Laboratories during the war. In 1952, Ottawa decided to form a new company, Atomic Energy of Canada Ltd. (AECL) as a spin-off from this establishment, signaling a Canadian ambition to build power reactors and commercialize nuclear energy.[71]

As of the 1940s Canada's electricity system was almost totally based on hydropower. But electricity consumption grew rapidly in the postwar years, and some provinces were running out of available sites for hydroelectric construction. The trend was most pronounced in Ontario, the country's wealthiest and most populous province. The Ontario Hydro Electric Power Commission, a provincially owned utility, responded by shifting its focus from hydroelectricity to constructing coal power plants. The year 1951 was important in this regard, as two large coal-fired steam plants were completed: the Richard L. Hearn station on the Toronto waterfront and the J. Clark Keith station in Windsor. These coal projects, which required substantial investments in steam technology, prepared Ontario Hydro for the nuclear age. In November 1953, AECL's nuclear scientists invited the utility to participate in a feasibility study for a pilot nuclear power plant. By that time, AECL had accumulated extensive expertise in nuclear technology, particularly heavy-water reactors. However, it lacked relevant skills in steam and electrical technology. The nuclear experts reasoned that cooperating with Ontario Hydro could compensate for this.[72]

In 1957, AECL and Ontario set up the joint Nuclear Power Plant Division (NPPD). Employing dozens of engineers from both agencies, it became a dynamic melting pot for two very different technological cultures: those of nuclear science and steam engineering. The engineers' collaborative effort

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eventually resulted in the CANDU reactor type, which was first tried out at Douglas Point on the shores of Lake Huron. Construction began there in February 1960, laying the groundwork for Canada's commercial nuclear program.[73]

Nuclear Steam for East Asia and the Global South

Before 1954, East Asia and the Global South had difficulty initiating work on nuclear power due to extensive secrecy policies that prevented them from obtaining scientific and technical information from the United States, Britain, and Canada. Another obstacle was that most "developing countries," as they were called, lacked steam-related experience. The countries that did manage to launch full-scale reactor projects at an early stage largely coincided with those that had previously built large coal power plants.

Starting in 1956, the Japan Atomic Energy Commission (JAEC), led by media mogul Matsutarō Shōriki, initiated negotiations with several foreign governments aiming for nuclear technology transfer from the West. A contract was eventually signed with Britain, paving the way for construction of a Magnox gas-graphite reactor at Tokai-Mura on the Pacific coast. The British subsidiary of General Electric cooperated with Fuji Electric on this project.[74] However, JAEC and the utility were not impressed with the British technology and opted not to build any further gas-graphite reactors. Looking for alternative designs, Japanese utilities viewed US light-water reactors as the most promising. For the time being, however, no new reactor projects were initiated in Japan.

In October 1964, India began constructing a US-designed nuclear power plant at Tarapur, located north of Bombay on the coast. General Electric was chosen to provide two 150 MW boiling water reactors modeled on the Dresden NPP. Bechtel, the US construction and engineering firm that built the Dresden NPP, built the Tarapur plant as well.[75] In parallel, India signed an agreement with Canada's AECL to purchase a CANDU reactor. This paved the way for the Rajasthan Atomic Power Station (RAPS) in southern India. This station would form the basis of the Indian nuclear program, with several more reactors subsequently added to the site. By the end of the 1960s, however, construction of the first reactor was far behind schedule and still incomplete. As a result, the future of nuclear power in India appeared uncertain.

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Several other countries in the Global South showed interest in the atom, but for the time being none of them managed to initiate a large-scale reactor project. In 1960, Brazil's National Nuclear Energy Commission announced plans to "ask bids for a 150-MWe power reactor to be built on the Mambucaba river near Angra dos Reis," with Brazilian firms set to undertake 30 percent of the project. But nothing came of these plans, at least for the time being. After a few years of atomic euphoria in Brazil, a 1963 government report calmly concluded that nuclear power plants did not make economic sense, at least not in a Brazilian context, "given the country's extensive hydroelectric capacity."[76] South Africa came to a similar conclusion in 1962, determining that "there would be no economic advantage under present conditions for the substitution of nuclear plants for conventional stations." Coal power was found to be much more economical.[77] Most atomic agencies in the Global South confined their activities to installing research reactors. These allowed numerous countries—from Argentina to the Congo—to develop knowledge about fission and radiation without having to engage in the complexities of steam engineering.[78]

Scaling Up the Nuclear Steam Engine

Overall, there was considerable global uncertainty about the future of nuclear energy in the early 1960s. Many were frustrated by the difficulties of making the technology work and, in particular, ensuring its competitiveness vis-à-vis coal power. In 1960, the International Atomic Energy Agency (IAEA), which had been formed in 1957, concluded that earlier appraisals had "underestimated the seriousness of the technological problems and were unduly influenced by transient economic and political factors."[79] Two years later the *Financial Times* declared that earlier enthusiasm and optimism in all things nuclear had given way to an "atomic ice age." A sense of crisis was omnipresent in many countries, from the United States and the Soviet Union to Britain, France, and Germany, as well as in smaller countries like Sweden and Switzerland.

A central dilemma had to do with the envisioned scale of civilian nuclear facilities. Throughout the 1950s many stakeholders had thought of nuclear power as a flexible technology capable of supplying heat and electricity on both small and large scales. Large nuclear power plants were not necessarily regarded as the ultimate goal. Small reactors were considered attractive in

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a variety of settings, not least in cities. Accordingly, municipal actors were often more enthusiastic about the new technology than large utilities and national electricity boards. From New York and Moscow to Stockholm and Berlin, they saw nuclear power as a suitable way to meet burgeoning urban energy needs and reduce air pollution.[80] Rural areas also dreamed of nuclear energy, as exemplified by the Elk River nuclear project in the United States, a 22 MW plant proposed by a rural electric cooperative in 1955. In early 1962, a group of Alaskan utilities likewise expressed interest in building small reactors for their sparsely populated state.[81] Moreover, small, mobile nuclear reactors were deemed suitable for installation in remote, harsh environments. Around 1960 the US military installed a 2 MW reactor for heat and electricity supply at its Camp Century, Greenland, and a 1.75 MW unit at the McMurdo research station in Antarctica.[82] Small reactors were also hailed as a perfect fit for developing countries, whose overall electricity needs were not yet that large.

In the course of the 1960s, however, the interest in small reactors gradually dwindled, giving way to decidedly larger projects. In hindsight, it is tempting to interpret this shift from small to large as a natural and inevitable transition. In fact, the increase in scale was not an inherent necessity. A closer look reveals that the push for larger projects was primarily a response to external pressures and intensifying competition linked to developments in the coal industry. Simply put, the trend toward larger fossil fuel plants forced the nuclear industry to scale up as well.

The art of building fossil-fueled power stations had advanced steadily from the turn of the century, when the first steam turbines saw the light of day. These machines gradually increased in size and capacity during the first decades of the twentieth century. In the United States, Chicago's Commonwealth Edison pushed the development by urging its equipment supplier, General Electric, to build ever larger turbines. By 1911, 5 MW turbines had given way to 12 MW machines, and 30 MW units were soon installed. Other utilities followed Chicago's lead, purchasing large turbines from GE and Westinghouse. Turbine capacities continued to grow rapidly during the 1920s. By the end of the decade, the largest turbine-generator sets had reached an impressive 160 MW. By 1956, US utilities had installed units as large as 300 MW, and shortly thereafter, they ordered 500 MW units. This scaling up resulted in significant efficiency gains.[83]

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Similar progress was seen in boiler manufacturing. During the interwar years the leading US suppliers, Babcock & Wilcox and Combustion Engineering, improved fossil boiler technology through a number of key innovations, such as the use of pulverized coal and the design of water-cooled furnace walls. This allowed manufacturers to increase operating temperatures and pressures, thereby improving thermal efficiency (that is, the percentage of coal's primary energy content that could be turned into electricity). In 1903, a typical boiler operated at a pressure of 12 atmospheres and a temperature below 300°C; they still had a lot in common with James Watt's eighteenth-century steam engines. By the mid-1920s, some boilers already operated at pressures up to 100 atmospheres. By the late 1930s the use of molybdenum steel in boilers allowed operating temperatures to approach 500°C. While the thermal efficiency of Thomas Edison's pioneering coal power station, built in 1882, was only 2.5 percent—a huge waste of energy!—it had risen to about 20 percent in boilers installed in 1940. The average thermal efficiency of US boilers climbed to 33 percent in 1965, and the development of "supercritical" boilers paved the way for further gains. In 1957, the Ohio Power Company set a new record with a boiler operating at 310 atmospheres and 620°C, achieving 40 percent thermal efficiency.[84]

The emerging nuclear industry had to adapt to these advances in coal power plant construction. In light of the efficiency gains achieved in the fossil fuel industry, a new consensus emerged that only large-scale nuclear power plants would be able to compete successfully with coal power plants.[85] Scale was increasingly identified as the key to profitability. Nuclear boosters were convinced that the fixed costs of a nuclear station, measured per unit of power, would decrease more rapidly than those of a coal power plant as reactors were scaled up. The US Federal Power Commission agreed, predicting that "the capital cost disadvantage of nuclear plants in comparison with conventional [i.e., fossil] plants will be less significant for larger plants."[86]

There was only one problem with large nuclear power plants: They brought new safety concerns. Larger reactors were inevitably harder to control. Additionally, they produced larger volumes of steam, increasing the plant's dependence on forced (pump-driven) circulation. If the coolant pumps stopped working for any reason, natural circulation of water and steam would not suffice to cool the core. At the same time, larger volumes of uranium fuel in the reactor meant that the core would overheat

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more quickly in the event of a cooling failure.[87] Overall, while core meltdowns seemed fairly manageable in small nuclear plants, they could be catastrophic in larger reactors. Starting in 1966, AEC safety experts began discussing a scenario in which the immense heat content of the fuel in a large reactor would cause it to melt through the bottom of the reactor vessel and then through the concrete floor at the bottom of the reactor building. This would result in the fuel escaping the containment. The phenomenon was referred to as the "China syndrome." The experts concluded that, given such a risk, the containment principle must be supplemented by additional safety measures. In particular, a plant's emergency core cooling system (ECCS) would need to be completely reliable.[88]

These problems sparked much internal debate among the AEC, the equipment suppliers, and the electric utilities. The AEC's Advisory Committee on Reactor Safeguards (ACRS), in particular, took a critical stance, pointing out the obvious risks associated with larger reactor designs. The ACRS often explicitly recommended against approving a new reactor design, citing safety concerns. Reactor manufacturers grew increasingly worried, fearing that additional safety requirements would erase the cost-efficiency gains achieved through the transition to larger reactors. They complained about what they regarded as an overly conservative—or, as one critic put it, "ridiculously cautious"—approach from the ACRS.[89] Together with the utilities, they lobbied the AEC to lower the safety requirements, pointing to America's rapidly growing energy needs and arguing that a too-cautious approach to nuclear safety might jeopardize the nation's electricity supply. The AEC found itself caught between its roles as promoter and regulator of the nuclear industry. Ultimately, it chose a contradictory approach: first approving construction of the proposed reactors and then scrutinizing the feasibility and safety of the designs, assuming that any shortcomings could be resolved later.[90]

The Commercial Breakthrough

It was on this shaky basis that General Electric, in December 1963, announced that it had sold a 515 MW boiling water reactor to Jersey Central Power & Light, an investor-owned utility, for a new power plant at Oyster Creek. GE agreed to build the facility for only $66 million, an incredibly low price compared to earlier reactor sales.[91] To be sure, actual costs were much higher

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than that, but GE had decided to try out a bold new sales strategy: Oyster Creek would serve as a "loss leader," meaning the vendor would accept a loss on this project in the hope that future market expansion would make up for it and pave the way for profitability. Westinghouse, not to be left behind, followed GE's example, and the competitive rivalry between the two companies stimulated a surge in reactor sales.

By late 1964 the impression was that the loss-leader strategy was working. As it seemed, the "atomic ice age" was over. More and more US utilities decided to invest in nuclear steam engines, and the reactors grew ever larger, eventually reaching over 1,000 MW. By 1967 a "great bandwagon market" for civilian nuclear power plants was evident in the United States. That year, General Electric alone received no fewer than thirty-one orders.[92] Lingering concerns that the technology was not mature and that a number of key safety challenges had not been satisfactorily addressed did not stop the new trend. The AEC continued to tentatively approve reactor designs that had not yet been proven safe; optimism prevailed that all concerns would be addressed in due time before the plants were taken into operation.

On the international scene, the new commercial dynamics in the United States had two major consequences. First, it convinced electric utilities in Canada, Europe, the East Bloc countries, Asia, and elsewhere that nuclear power had become competitive with fossil power plants. This encouraged the construction of more nuclear stations. At the Third International Conference on the Peaceful Uses of Atomic Energy, held in Geneva in September 1964, a new optimism was unmistakably in the air. Everyone seemed to agree that commercial nuclear power had finally achieved a breakthrough.

Second, US developments suggested that, of all the proposed reactor models, light-water reactors—specifically, pressurized water reactors (PWRs) and boiling water reactors (BWRs)—were the most economical. This was a painful realization for those who had already invested billions of dollars in alternative reactor designs. Under pressure from profit-oriented electric utilities, governments and atomic energy boards of countries such as France, Germany, Switzerland, and Sweden reluctantly abandoned their gas-graphite and heavy-water programs, shifting to light-water technology.[93] The heavy-water and gas-graphite programs pursued by the communist countries likewise receded into the background.[94] Britain, too, considered giving up its gas-graphite reactor line. However, the government eventually opted to

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subsidize domestic development to maintain technological independence.[95] The UK aside, Canada was the main exception that proved the rule; its heavy-water program had already gained so much momentum that abandoning it seemed unrealistic.[96] In the Global South, India and a few other countries maintained an interest in heavy water. However, most southern nations, along with East Asia, turned to light-water technology.

From the late 1960s on, more and more nuclear steam engines were built across the world. Following the unprecedented surge in American nuclear investment, the United States surpassed the United Kingdom in 1967 in terms of the total number of electricity-generating reactors that had begun construction since the dawn of the atomic age. By 1972 more than one hundred civilian reactors were already in operation or under construction in North America. Continental Western Europe reached the same level five years later. Large reactors were built in France, Germany, Italy, Spain, Switzerland, Austria, Belgium, the Netherlands, Sweden, and Finland. The Soviet Union followed a similar pattern, with a delay of a few years. Additional Soviet-designed reactors began to be erected in East Germany, Bulgaria, Hungary, Czechoslovakia, and Poland. In East Asia, Japan led the way, with eighteen construction starts by 1972. That same year, South Korea and Taiwan began construction of their first electricity-generating nuclear plants. In the Global South, India, Pakistan, Argentina, and Brazil had begun erecting their first reactors by 1971. Five years later construction was underway in Mexico, Iran, South Africa, and the Philippines.[97]

Yet what looked like an emerging golden age of civilian nuclear energy would not last for long. One major reason was the unresolved safety issues stemming from the attempts to merge nuclear and steam engineering. These issues proved more difficult to cope with than expected, and they would continue to haunt the global nuclear industry for decades. Eventually, the microlevel concerns over reactor safety discussed in this chapter entered the public realm, contributing to a dramatic politicization of nuclear energy in the United States, Western Europe, East Asia, and elsewhere. In the meantime, challenges of a different kind made themselves felt. At the meso level, nuclear plant builders struggled to integrate their facilities into the natural environment. And at the macro level, the need to cope effectively with nuclear fuel posed obstacles to the industry's growth and survival. These dilemmas are the focus of the next two chapters.

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Conclusion

During the opening ceremony of the United Kingdom's pioneering Calder Hall nuclear power station in 1956, Queen Elizabeth II marveled at how, in the industrial age, human civilization had "seen one technical revolution succeed another with astonishing speed":

> Within the span of a few generations, our way of life has been transformed beyond anything our forefathers could have imagined. The age of steam was succeeded by an age of such startling achievement that we who are close to it can hardly realise that so short a period encompassed the invention of the motor car, the wireless set, the aeroplane, and much else besides which we now take for granted. So quickly have we learned to accept the pace of modern development that we have been in danger of losing our sense of wonder. That sense has been dramatically restored by the advent of the atomic age.[98]

The Queen's claim that the age of steam had been "succeeded" by another age was ambiguous. After all, the fission energy released by the uranium in the Calder Hall reactors was used to boil water. The resulting steam powered a turbine and an electric generator. It was a nuclear steam engine.

The same was true for all other nuclear power plants built worldwide from the 1950s onward. The plants were the outcome of intense efforts to combine two very different fields: nuclear science and coal power plant construction. At the outset, many scientists and engineers considered the merger straightforward. Some even ignored the challenge altogether, because it seemed so banal. The nuclear scientists were interested in trying out increasingly advanced reactor principles, based on ideas and possibilities derived from physics and chemistry. How to turn the heat produced in the reactors into practically useful electricity was a much less intriguing question. Meanwhile, engineers with expertise in coal power plant design were confident that they could build a nuclear power plant through relatively minor adaptations of a fossil plant: all that was needed was to replace the conventional boiler with a reactor. To them, a nuclear power plant was "just another steam engine."[99]

As it turned out, both sides underestimated the difficulties that lay ahead when it came to merging the two technological traditions. The hybridization of nuclear science and steam engineering became messy, and it introduced a new set of risks to the electricity industry. It took until the mid-1960s for nuclear power to achieve its commercial breakthrough—and that breakthrough was highly ambiguous. Engineers found the technology

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frustratingly difficult to implement, and they were concerned by growing safety requirements and rising costs.

The marriage of nuclear science with steam engineering was in no way predetermined. The two were not necessarily "meant to be." In fact, nuclear energy repeatedly seemed to resist its own development, as evidenced by cost escalations and the realization that nuclear reactors posed unique dangers. Had they wished to, governments, manufacturers, and electric utilities could have easily rejected the new technology; there was no lack of sound rational arguments that could have supported such decisions. Many countries ultimately did reject nuclear energy, choosing not to progress beyond research and experimental facilities. Few of them would regret that choice.

In theory, the engineers could also have invented nuclear power plants that were not steam engines. Had the development not been so rushed, it would have been natural to explore alternative technological pathways into the civilian atomic age. These alternative paths could have taken the nascent nuclear industry in different directions. Historian Joachim Radkau has noted that if gas-cooled reactors had prevailed in the global market, gas turbines would have been a more logical choice than steam turbines for generating nuclear electricity. This would have avoided many of the problems associated with the "steam" part of nuclear power plants. However, gas turbines were a novel technology at the time and would have required long-term, risky investments.[100]

Around 1960, moreover, there was an intriguing debate in the engineering community about the prospects of "direct conversion"—using advanced thermoelectric or thermionic methods to convert nuclear heat to electricity—reflecting a vision of a civilian atomic age that would not have been a new age of steam.[101] But reactor vendors and electric utilities were unwilling to wait for such technological marvels. They wanted to design and build nuclear power plants now, not in a few decades. This made the steam trajectory, with its industrial maturity, difficult to resist.

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2 Envirotechnical Entanglements

The hybridization of nuclear and steam technologies had far-reaching consequences not only for the design of nuclear power plants but also for the interplay between such plants and their natural environments. The laws of thermodynamics dictated that only around one-third of the heat generated in a nuclear reactor could be converted into electricity. The remaining two-thirds would have to be disposed of somehow. Plant builders solved this problem by adding a "condenser," a heat exchange system that used water from an external source—a river, lake, or sea—to cool and condense the steam while absorbing the heat. This connection between the nuclear power plant and the waterbody—the "ultimate heat sink," as the engineers called it—blurred the boundary between technology and nature, generating complex envirotechnical entanglements while effectively extending the territory of the nuclear power plant far beyond its official fences.

It was absolutely necessary that the condenser operated smoothly and that cooling water from the ultimate heat sink was available at all times. The worst nightmare for any nuclear engineer was that the flow of water would be interrupted for one reason or another. In such a situation, the uranium fuel in the reactor would overheat, potentially resulting in a core meltdown. Not even a minute of interrupted supply could be tolerated, because the reactor would then start to heat up in a dangerous way. For this reason, the engineers devoted considerable attention to the design of the cooling system and its integration with the natural environment.

Very large external water flows needed to be mobilized for nuclear cooling. The condensers of a standard 1,000 MW reactor required about 50 cubic meters (13,000 gallons) of water *per second*—comparable to the flow of a mid-sized river or a large irrigation canal.[1] To facilitate this wet nuclear

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extractivism, nuclear builders invested heavily in canals, dams, locks, pools, dikes, and pumps—technologies that, in and of themselves, had little to do with nuclear engineering. Yet no atoms could be split without them. Microengineering at the level of atoms and nuclei was only possible through macroengineering that manipulated large-scale water flows. This hybridization of nuclear and hydraulic engineering would prove to be just as critical—and fateful—to nuclear energy's career as the marriage between nuclear science and steam engineering.

Atomic Rivers

The history of nuclear siting worldwide is interesting to follow. Early reactors were small and built for research and experimental purposes. They only needed a negligible amount of, if any, external cooling water. These reactors were constructed in urban settings in close proximity to institutions conducting nuclear research, such as in Chicago, Moscow, Paris, and Stockholm.[2] As the plants grew in size, they were erected at sites where larger volumes of water could be extracted. Major rivers, in particular, attracted the attention of the world's nuclear visionaries. In the United States, the Mississippi and its tributaries saw the arrival of nuclear builders early on, as did several East Coast rivers. In the Soviet Union, the Don, Dnieper, and Volga basins were exploited. In Western Europe, the Rhine emerged as a nuclear mecca, with Swiss, German, French, and Dutch utilities planning several dozen plants along the main river and its tributaries. France also turned to the Rhône and Loire basins. Italy harnessed the Po. Other rivers of interest included the multinational Danube and Elbe, whose cooling potential captured the imagination of nuclear engineers on both sides of the Iron Curtain. In the Global South, Argentina targeted the Paraná River, while India used a reservoir built on the Chambal River to cool its Rajasthan Atomic Power Station.

Extracting fifty cubic meters of water per second and ensuring an uninterrupted flow was no easy task. Fortunately, the nuclear builders could learn from prenuclear hydraulic engineering efforts. For instance, they could draw from a well-established tradition of large-scale water withdrawal dating back to ancient Mesopotamia and other "hydraulic civilizations." Large-scale irrigation schemes and prenuclear industrial efforts to harness natural waterways for mechanical and electric power offered particularly relevant models.

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It is no coincidence that many riverine nuclear plants relied on specially constructed canals, into which the river water was diverted before being pumped into the plant; water withdrawal for irrigation and industrial use had been arranged that way for millennia. Similarly, the pumping arrangements used to lift the water and move it through the nuclear plant's condensers were modeled on systems already used in coal power plants, steel mills, and chemical complexes.[3]

Moreover, nuclear builders were able to make productive use of what earlier hydraulic engineers had accomplished at specific riverine sites. As they searched for suitable locations for their nuclear projects, utilities avoided pristine rivers as much as possible, because these rarely provided a reliable year-round water flow. Instead, they sought out waterways that had already been "tamed" through past hydraulic engineering activities such as dredging, damming, diking, rectification, and canalization. It is no coincidence that the world's main nuclearized rivers feature prominently in histories of river regulation. The Upper Rhine, for example, is not only a river of central importance in the history of nuclear power but also an iconic landscape in prenuclear water history: It was here that Johann Gottfried Tulla famously pioneered his groundbreaking approach to river rectification in the early nineteenth century.[4] Two catastrophic floods in 1840 and 1856 sparked similar developments on the Rhône, a mighty stream that a century later emerged as France's most nuclearized river.[5] In the United States, several large nuclear plants, including the infamous Three Mile Island station, were built along the Susquehanna River, whose "particular geology and variable water flows," as Christopher Jones writes, had caused much trouble for those trying to use the river for transportation or power generation. "During the spring melt, the river often rose significantly and flooded. During the dry season in late summer and early fall, the great river was frequently reduced to a trickle." In the early twentieth century, hydroelectric companies tamed the wild river by damming it at several locations, producing a much more regular flow.[6] This prepared the Susquehanna for its later role in the atomic age.

The presence of hydropower plants on riverine sites offered an additional benefit for nuclear construction. Utilities could use these facilities as backup sources of electricity; in the event of an external power outage, the hydroelectric station could safely provide power to the nuclear plant's cooling water pumps. For example, the appeal of Beznau in Switzerland as

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Figure 2.1
Artwork celebrating the completion of the Fessenheim hydropower plant in France. Fessenheim is a well-known place in the history of nuclear power in Europe. What is less well-known is that the construction of a nuclear power plant at this site in the 1970s was preceded—and facilitated—by the construction of a hydroelectric plant in the 1950s, next to the future nuclear site. *Source*: Photo by the author, August 2023.

a nuclear site hinged on the presence of an old dam on the Aare River built around the turn of the century and equipped with hydroelectric turbines.[7] France's Fessenheim NPP (built 1971–1978) was another nuclear power station erected next to a hydropower plant, which had been completed in 1956 in conjunction with construction of the Grand Canal d'Alsace (figure 2.1).[8]

In numerous cases, however, the preferred river sites did not meet the utilities' expectations. For example, the water flow might be too irregular. In such cases, the nuclear builders had no choice but to undertake their own hydraulic engineering efforts, taming the river by damming, diking, and canalizing it. West Germany's Gundremmingen NPP exemplifies this challenge. The Upper Danube, which would serve as the plant's cooling water source, had not yet been canalized when RWE and Bayernwerk, the two utilities in charge of this reactor project, arrived, but the nuclear undertaking spurred efforts to dam the river both upstream

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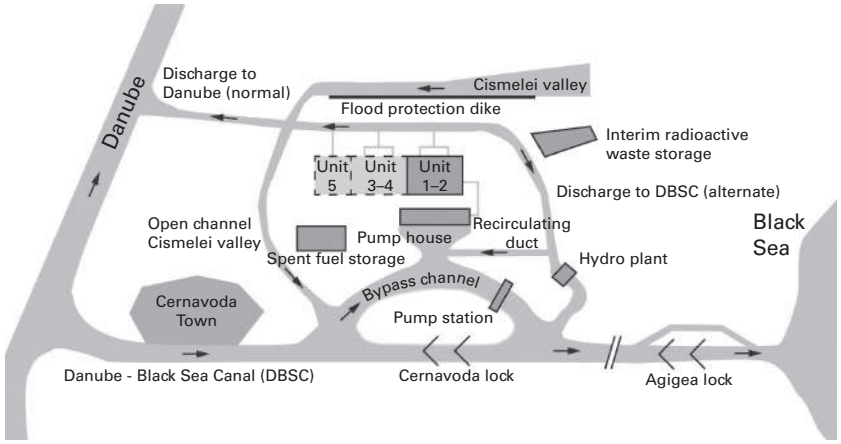

Figure 2.2
Water flow scheme for the Cernavoda NPP, Romania. The plant was built on the Danube and the Danube-Black Sea Canal. *Source*: Author's own work/Red Geographics.

and downstream of the station. The dams were equipped with hydroelectric turbines that were taken into operation in conjunction with the first nuclear reactor. Some of the Soviet Union's early nuclear sites, including Novovoronezh in southern Russia, which pioneered the Soviet version of the pressurized water reactor (the VVER reactor type), likewise hinged on engineers' ability to "improve" the nation's rivers.[9]

It was common for nuclear construction to be carried out in parallel with hydraulic works aimed at improving navigational conditions. Austria's Zwentendorf NPP, for example, was built in parallel with a major scheme to canalize the Danube.[10] Further down the same river, the erection of Romania's first nuclear power plant, the Cernavoda NPP, proceeded alongside the excavation of the Danube-Black Sea Canal. Nuclear and hydraulic engineers collaborated on how to combine the construction of this new waterway and the reactors. They eventually picked a site for the plant just 1.5 km from the first lock on the canal. They built a smaller bypass canal around the lock to provide the nuclear reactors with sufficient cooling water, along with a specially designed intake canal and a distribution basin. The heated cooling water was discharged through another set of artificial streams (figure 2.2).[11]

Large rivers, such as the Danube, seemed to provide consistent access to cooling water. Along other waterways, there was a fear that the available

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water might not suffice. At these sites, nuclear plant builders sought to increase the cooling capacity with specially designed "cooling ponds." These provided backup cooling capacity, reducing the risk of having to shut down a reactor due to water scarcity. The idea of storing water in a reservoir was not new. It dated back to ancient hydraulic societies around the world. In arid regions such as Mesopotamia, large-scale reservoirs had historically played a crucial role in reducing the risk of famine.[12] Reservoirs were also critical to early water-powered industrialization, ensuring that factory wheels did not grind to a halt when river levels changed. From the late nineteenth century onward, reservoir technology advanced further in connection with the construction of hydroelectric dams.[13] These historical experiences of water storage inspired the world's nuclear planners.

However, large-scale nuclear facilities required enormous volumes of water. This meant that nuclear water reservoirs had to be exceptionally large, covering many square kilometers. Consequently, they could only be built in areas with large tracts of cheap and preferably uninhabited land. Their sheer size radically altered the riverine landscape. In the United States, many cooling ponds were built by damming streams in hilly regions. This gave rise to new artificial bodies of water such as Harris Lake in North Carolina, which served the Shearon Harris NPP. Such "nuclear lakes" became popular with the local population, because they could be used for recreational activities such as fishing, swimming, surfing, and hiking. Spanish nuclear builders followed the same pattern at their Almaraz NPP, built on the Tagus River.[14] Soviet engineers built similar ponds at sites such as Kursk and Smolensk, where large parks of reactors mushroomed in the 1970s and 1980s. In southern Ukraine, the Tashlyk River was dammed to create a pond that served a pumped-storage hydropower plant and agricultural irrigation, in addition to nuclear cooling. At Novovoronezh (figure 2.3) and Chernobyl the Soviets built cooling ponds in the form of elevated reservoirs supported by huge earthen dikes running parallel to the river. This design required powerful pumps to lift water from the river into the pond.[15] The British, meanwhile, built "tidal reservoirs" for their Berkeley and Oldbury NPPs, which were constructed on the shores of the Severn. They consisted of a "low wall . . . built on the rock shelf fronting the site to impound river water during the high tide period which will be used during the low tide period." The arrangement ensured that sufficient volumes of cooling water would be available at both high and low tide.[16] The British model appears to

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Figure 2.3
View from the "atomic city" of Novovoronezh, where the Soviet Union pioneered several generations of its VVER pressurized water reactors. The first four reactors built at this site relied on the Don River and several cooling towers for cooling. In preparation for the addition of the plant's fifth reactor, seen here in the upper left, Soviet hydraulic engineers constructed a 5 km^2 cooling pond. The pond was supported by a 10-meter-high earthen dam. In connection with the pond's construction, the engineers diverted the Don River into a new course. The cooling pond was also integrated into the urban planning of the adjacent nuclear town, where the plant workers lived, and its embankment became the most popular place for a Sunday afternoon stroll. In this way, the nuclear station, the river, the cooling towers, the cooling pond, and the nuclear town became part of a single envirotechnical system. *Source*: Wikimedia Commons.

have inspired later Soviet projects. The Soviets built ponds similar to those on the Severn on the Volga, Don, and Dnieper Rivers, including at the now infamous Zaporizhzhia site in Ukraine. These ponds took the form of segments of rivers cut off from the main stream by dikes.[17]

Where ponds were not a realistic option, the engineers built cooling towers. These turned the ancient technology of water storage into distinctly modern artifacts that radically altered the visual appearance of the nuclear power plant and the surrounding landscape. Like a cooling pond, a cooling tower reduced, but did not eliminate, the reactors' dependence on continuous external water supplies. Whereas a 1,000 MW nuclear reactor equipped with a "once-through" cooling system (no cooling towers) required fifty

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cubic meters of water per second, a plant with a "recirculating" system (with the recirculation happening in the towers) needed only two to three cubic meters. This made it possible to build nuclear power plants at sites that would not otherwise qualify. The drawback, aside from the sheer cost of the towers, was the continuous loss of about a cubic meter of water per second to evaporation. Another disturbing fact was that cooling towers were found to decrease the overall thermal efficiency of the nuclear steam engine.[18]

Nuclear Thermopolitics

Wet nuclear extractivism fueled controversy. Social and political tensions arose at numerous sites, sparking early opposition to nuclear power. These water-centered conflicts, which preceded the more well-known antinuclear struggles of the 1970s, mark the beginning of a more critical engagement with the atom, especially in the United States and Western Europe.

The main threat, in the critics' eyes, was the discharge of large volumes of warmed cooling water into rivers and lakes. In the United States, the debate about this phenomenon, which opponents conceptualized as "thermal pollution," began with a conflict that arose in the mid-1960s between the AEC and the Federal Wildlife Service (FWS). Supported by a community of concerned anglers and conservationists, the FWS was worried about the future of aquatic life near large-scale nuclear power plants. Up until then, nuclear energy had been considered environmentally friendly compared to polluting fossil stations and hydropower plants, which disrupted a river's water flow and ecosystem. However, as nuclear power plants grew in size, the FWS began to fear that they might damage the environment. It was well-known that many fish species were sensitive to changes in water temperature. Their metabolism, reproductive cycles, respiratory rates, and other vital functions might be jeopardized, while a "drastic or a sudden shift in temperature could be lethal."[19] The concerns grew in tandem with the emergence of the wider environmental movement and attempts to inscribe environmental protection more firmly into law. The 1965 Federal Water Quality Act became an important tool in this context. The act, which encouraged states to set standards for traditional pollutants and water temperatures in rivers and coastal waterways, was passed at the same time that nuclear power saw its commercial breakthrough. The prospect of hundreds of ever larger nuclear reactors sparked widespread concern about the

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potentially devastating effects of thermal pollution on the nation's aquatic environments.

The thermopolitical debate reached its first critical juncture in November 1966, when a consortium of ten utilities applied for permission to build the 514 MW Vermont Yankee Generating Station on the Connecticut River, which formed the border between Vermont and New Hampshire. Five miles downstream from the proposed construction site, the river flowed into Massachusetts. Officials were deeply worried. "Vermont will receive a million-dollar injection into its economy. Massachusetts will receive hot water," complained Elliot L. Richardson, Massachusetts's attorney general. James B. Oakes, attorney general of Vermont, suggested that the problem could be solved with the help of cooling towers. Such towers would reduce the nuclear plant's water withdrawal and discharge, thereby keeping water temperature increases to a minimum. The utilities opposed this solution, maintaining that cooling towers were both "unnecessary and too costly." Pressure mounted on the AEC to take action, but the Commission insisted that it was responsible only for issues related to radioactive pollution, not thermal pollution. Critics suspected that the AEC resisted stricter environmental standards because of fears that they would hinder the expansion of nuclear power.[20]

The conflict continued with no obvious resolution in sight. In February 1968, the Senate Committee on Public Works' Subcommittee on Air and Water Pollution organized a series of hearings to come to grips with the situation.[21] The AEC faced heavy criticism from many sides but maintained its position. New Hampshire then took the Vermont NPP case to court, arguing that the AEC must "consider thermal pollution in its decision to issue the permit to Vermont Yankee." In January 1969, the court of appeals denied that assertion.[22]

By this time, however, the broader environmental debate in the United States had intensified to an unprecedented degree, and an increasing number of stakeholders were voicing concerns about thermal pollution. In parallel, utilities initiated construction of more and more nuclear power plants along the nation's rivers. By 1970, media dramatically highlighted what was at stake, suggesting that "by the end of the decade our rivers may have reached the boiling point," evoking the image of "an ultimate cataclysm."[23] US scientists involved in research on thermal pollution and its effects were usually more measured in their assessment, but the public and political

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debate seemed unstoppable. The AEC began to fear that nuclear thermopolitics might negatively impact public acceptance of nuclear power, thereby endangering America's atomic future.[24]

In the meantime, thermal pollution was problematized in Western Europe, too. There, Switzerland emerged as an early mover in addressing the dilemma. In December 1964, Nordostschweizerische Kraftwerke (NOK), a utility, applied for permission to erect the Beznau NPP on the Aare River. The head of the Cantonal Office of Water Protection, Friedrich Baldinger, pointed out that warming the Aare could be disastrous for the many fish species living in the river. He asserted that the country's waterways were already in a precarious state and that discharging large volumes of warmed cooling water from nuclear facilities would worsen the situation. Massive fish kills could not be ruled out.[25] Despite this dire assessment, Switzerland's federal authorities gave the Beznau plant the green light because the country urgently needed the electricity.

Over the next few years, the Swiss followed the emerging debate over thermal pollution in the United States with unease. It was felt that the discharge of heated cooling waters might become an even more controversial issue in Europe, given the concentration of proposed nuclear power plants along a few key rivers. In 1967, the Swiss government appointed Baldinger to lead a commission to further investigate the problem and propose solutions. The experts sought to use scientific evidence to determine the "thermal capacity" of the High Rhine and its main tributary, the Aare River. Their report, completed in March 1968 but not publicly released until spring 1969, became the first in Europe to specify, in quantitative terms, acceptable levels of thermal pollution from nuclear power plants. The commission concluded that the returned cooling water must not be allowed to warm up the river by more than 3°C after complete mixing. The maximum permissible temperature was set to 25°C. Additionally, the temperature of the cooling water at the discharge point must not exceed 30°C, though temperatures up to 35°C could be permitted in exceptional cases.[26]

Several other European studies reached similar conclusions in 1969 and 1970. A scientific consensus formed around two key points: First, no nuclear reactor should be permitted to increase the temperature of the natural waterway on which it was built by more than a few degrees (usually 3°C); second, there must be a clearly defined limit on how warm a river's water could be at the point of discharge (usually between 25 and 30°C,

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depending on the local climate). However, the electricity industry did not accept these conclusions. The utilities continued to oppose any limitations on their planned nuclear stations. As in the United States, they also resisted the use of cooling towers as a technical fix, citing high costs and reduced operational efficiency of plants. They argued that cooling towers were only necessary at sites with water scarcity.[27]

The controversy peaked in 1970 and 1971. The focus was, in particular, on the Rhine. The transboundary nature of this river sparked a lively debate both nationally and internationally. Switzerland and the German state of Baden-Württemberg, building on an earlier track record of water diplomacy, sought to negotiate a fair distribution of the "heat load capacity" of the High Rhine and the Aare. The International Commission for the Protection of the Rhine (ICPR) and the European Parliament also began to discuss the problem and possible solutions.[28] The issue was framed in increasingly existential terms. A widely cited article in *Der Spiegel*, a German magazine, evoked cataclysms similar to those that proliferated in the United States. "By the end of the 1970s at the latest," the article predicted, the Rhine would "roll toward the sea as a cloudy, steaming broth":

> The Rhine water, heated to 40 to 50 degrees, spreads a foul smell of sludge, clouds of steam rise, the bank areas are bathed in billowing fog, only dimly penetrated by the sun. Then the last fish, which still miraculously defy the constant release of poison from the Rhenish industry, will have died from a lack of oxygen. Lukewarm drinking water flows into the big cities from the wells near the banks, and cold showers can only be taken by those who have cooling units in their bathroom. The riparian zones are affected by heat and humidity, and the climate and vegetation have completely changed.[29]

Although no large-scale nuclear power plant was yet operating on the Rhine, the implication was clear: If the nuclear industry were to realize its grand ambitions, steps would have to be taken to prevent the worst-case scenarios from becoming reality. Governments responded by organizing parliamentary hearings and preparing legislation. Once again, Switzerland led the way. In April 1970, the Aargau cantonal government informed Motor Columbus, a private company planning a nuclear power plant at Kaiseraugst on the High Rhine, that permission to use this river's water for nuclear cooling would be granted only under certain conditions. The company would have "to dissipate part of the waste heat through other cooling systems or to reduce the output accordingly if the plant's share of the

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Figure 2.4
The Cattenom nuclear power plant in France, built 1979–1992. When construction of this four-reactor plant began in the late 1970s, it was a given that it would be equipped with cooling towers. In this particular case, the recirculating cooling system also included the construction of an artificial lake (shown here) to further reduce thermal pollution of the Moselle River, from which the cooling water was sourced, and to reassure worried winegrowers downstream in Germany and Luxembourg. *Source*: Photo by the author, November 2021.

heat capacity of the Rhine river system is not sufficient to release the waste heat."[30] Then, in March 1971, the Swiss federal government, much to the dismay of the nation's utilities, decided to forbid the use of once-through cooling systems at all future nuclear power plants. Similar decisions were soon taken by other European governments. Reluctantly, European utilities began to accept the need for cooling towers (figure 2.4).[31]

There was a similar trend in the United States. There, Congress passed the Water Quality Improvement Act in early 1970 along with the broader National Environmental Policy Act (NEPA). These laws became powerful instruments in the hands of the Department of the Interior and the new Environmental Protection Agency (EPA), which were increasingly able to convince the AEC to take into account environmental issues in its nuclear licensing procedures, pressing utilities to adapt their plant designs to protect aquatic life.[32] State-level pollution control agencies became key actors in urging utilities to equip both old and new nuclear power plants with

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cooling towers or cooling ponds. As before, the utilities were reluctant to do so, because these hydraulic arrangements added significantly to plant construction costs while lowering the operational efficiency—and hence electricity sales—of the plants by around 6 percent. Many utility managers thought it was absurd that environmental concerns over a few species of fish should significantly influence the design of their nuclear power plants. But the "environmental revolution," as industry insiders called it, was unstoppable. Hence, the Minnesota Pollution Control Agency, for example, was able to force Northern States Power to install a closed-cycle cooling system at its Monticello NPP, which was erected on the Mississippi. Similarly, the Illinois Pollution Control Board required Commonwealth Edison to build a brand new 1,300-acre "cooling lake" before allowing the third reactor at the Dresden NPP to start up.[33] Another reluctant utility was the federal Tennessee Valley Authority (TVA). It fiercely opposed the implementation of the strict thermal limits advocated by the scientific community. The TVA insisted that its nuclear plants, which extracted cooling water from the Tennessee River, be permitted to raise the river's temperature by as much as 10°F (6°C), rather than 5°F (3°C), and allow the water temperature at the discharge point to reach 93°F (34°C). But by summer 1971, after negotiations with the federal authorities, the utility had to accept the Department of Interior's more stringent limits.[34]

During the first half of the 1970s, as cooling towers began to be erected at numerous sites, the European discussion shifted to the potential environmental and societal impacts of these structures. Adding one or more cooling towers increased the envirotechnical complexity of nuclear power plants. More land was needed, as well as additional pipes and canals to connect the hyperbolic reservoirs to the condenser. The sheer size of the cooling towers also raised concerns. Many were as tall as 180 meters, dwarfing everything around them. The towers radically altered Europe's riverine landscapes, making nuclear power plants visible from far away in a way that contrasted sharply with plants equipped with once-through cooling systems. This sparked local protests, especially among farmers, who feared that the immense plumes of water vapor emitted by the cooling towers would alter the local climate. There was much discussion about fog formation, in particular. Meteorologists further warned that releasing water vapor in large quantities could lead to "more rain and thunderstorms during the summer months, and to more black ice during the winter."[35]

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In Switzerland, the utilities in charge of planning the Kaiseraugst NPP reluctantly accepted the federal government's decision to prohibit once-through cooling. In July 1971, they applied for permission to redesign their plant with a recirculating cooling system centered on two 115-meter-tall cooling towers. This led to protests from the local population. Swiss newspapers reported that a "cooling tower war" was about to break out. The tourist industry, in particular, viewed the planned cooling towers as an "unacceptable impairment" of the landscape due to their immense size. Leading Swiss environmental organizations sided with the critics. Over time the emerging antinuclear movement came to see the cooling towers as symbols of a decidedly inhumane technology.[36]

In Germany, the protests focused on a planned nuclear power plant at Breisach in the Upper Rhine valley, where the river marked the border with France. Located in one of the country's prime wine-growing regions and only 30 km downstream from EDF's planned Fessenheim NPP, the Breisach NPP began to be intensely debated at the local and regional level from mid-1971. Winemakers and many others whose livelihoods depended on viticulture were "full of questions about the Breisach reactor and its potential to affect the region's precious and sensitive crops." The main fear was that the water vapor ejected from the cooling towers would cause "dense fog that would be trapped in the valley and block out its precious sunlight." The fog would also lead to more fungal diseases and more hail. Opponents were not against nuclear energy as such, but they criticized the proposed nuclear-hydraulic arrangements. They rejected "a technologically second-class solution for the disposal of excess heat," as a newspaper report put it in August 1972. In July 1973, Badenwerk, the responsible utility, announced its decision to move the proposed reactor away from Breisach, 20 km downstream to a new site near the village of Wyhl.[37] That project, however, would become even more contentious, as we will see in chapter 4.

In the United States, the heated debate about thermal pollution largely ebbed out as utilities agreed to equip their plants with cooling towers. However, the harsh political and public criticism of the AEC and the utilities' nuclear projects did not disappear. It merely shifted to a new concern: the threat of radioactive effluents released by commercial nuclear power plants. The bitter debate that unfolded over this problem was directly inspired by the thermal pollution debate. As historian Samuel Walker notes, "The thermal pollution issue laid the foundations for the radiation controversy and

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subsequent disputes over reactor safety. It was the first problem to raise widespread skepticism about the environmental benefits of nuclear power, and the doubts it stirred gradually expanded into other areas. It also undermined the credibility of the AEC. The agency's reluctance to take action against thermal pollution offered support to charges that it was indifferent to the environment. This fueled suspicions about its performance on other environmental issues that were apparent, for example, in the growing radiation debate."[38]

Reactors on the Beach

There was one seemingly straightforward way for utilities to avoid the problems that plagued inland nuclear facilities: Choose seaside locations. Coastal sites became immensely popular with nuclear builders around the world. To date, around 45 percent of the world's nuclear power plants have been built by the sea, and the share appears to be increasing in the twenty-first century.[39] All large-scale nuclear power plants in Britain, Sweden, Finland, the Netherlands, East Germany, Taiwan, China, South Korea, Japan, the Philippines, Brazil, Mexico, South Africa, the United Arab Emirates, Iran, Turkey, and Egypt—plus additional ones in the United States, Canada, France, West Germany, Spain, the Soviet Union, India, Pakistan, and Argentina—were built by the sea.

By tapping into the sea, reactors could access seemingly unlimited volumes of cooling water. The sea was generally colder than inland waters, a fact that translated into thermal efficiency gains and hence cost advantages. Moreover, thermal pollution was less of a concern on the coast than along rivers, because no drinking water supplies were at stake. Consequently, there was rarely any need to build cooling towers. This made coastal nuclear power plants both less expensive and less prominent in the landscape. There was no "smoke," and the typical coastal nuclear facility looked more like an electronics factory, a warehouse, or perhaps most of all, a temple—a sacred place far from everything—than an energy production site. California's San Onofre nuclear power plant was playfully compared to a beach ball.[40] Britain's and Sweden's coastal plants featured distinctly modernist architecture that conveyed a sense of national technological pride. They were "large, simple, and monumental," standing out "against the sea and horizon."[41] And in Tamil Nadu in India, beachgoers nowadays marvel

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Figure 2.5
The Kudankulam nuclear power plant in Tamil Nadu, India. *Source*: indiawaterportal .org/Wikimedia Commons.

at several "ethereal cream and ochre domes" in the distance. "They could be modernist Buddhist stupas but the more perceptive ones know that these are the definitive new structures of the Kudankulam Nuclear Power Plant" (figure 2.5).[42]

Yet, coastal sites faced their own problems. Besides having to cope with the potentially destructive impact of storms, hurricanes, and typhoons, the salty seawater increased the risk of corrosion of critical equipment and machinery.[43] Moreover, numerous sites had to cope with gradual and accelerating coastal erosion. Maritime fauna and flora posed another threat. Over the years, many coastal nuclear power stations encountered immense problems with algae and, worse, swarms of jellyfish "attacking" the cooling system.[44] Agglomerations of mussels were often discovered and had to be removed at great expense. Some nuclear operators feared that oil spills from passing tankers might jeopardize seawater-based nuclear cooling, prompting investments in additional safety arrangements. And while coastal locations were attractive for cooling purposes, they sometimes intersected seismic fault lines. This was the case at Fukushima and several other Japanese sites, as well as in places such as Taiwan, California, Crimea, Portugal, and Greece.

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Arguably the greatest challenge for coastal nuclear builders was that the seaside was rarely an empty space. Utilities had to establish the smoothest possible relationship with other human activities in the borderland between land and sea, which was often easier said than done. One particular problem was the growing popularity of the seaside as a recreational and tourist destination in the postwar decades. Beach tourism exploded in the 1960s and 1970s—the same period that saw the breakthrough of civilian nuclear energy. This generated tension and conflict. It is no coincidence that the Mediterranean, the world's most popular destination for beach tourism, is also the least exploited by nuclear builders in the Western world. Only two nuclear power plants have (so far) gone into operation on Mediterranean shores: the Latina NPP in Italy and the Vandellòs NPP in Spain. This number can be contrasted with the massive nuclearization of the much smaller Baltic Sea, which came to host seven large nuclear power plants boasting no less than twenty-two commercial reactors, and the Atlantic coasts of Europe and the United States, where dozens of reactors were built.[45]

Opposition to coastal nuclear power plants was formidable in the Mediterranean and on the US Pacific coast. Italy, an early mover in nuclear construction, has one of the longest coasts in Europe. After the government launched a massive nuclear expansion program in the wake of the first oil crisis, most observers thought it was inevitable that the coast would come to host numerous large-scale nuclear facilities. Inland sites were considered more problematic, since the Po and other rivers were heavily used for irrigation, drinking water supply, and industrial purposes. Besides, the flow in most Italian rivers was notoriously irregular and unpredictable. ENEL, the state-owned Italian electricity monopolist formed in 1962, initially proposed building one nuclear plant on the Adriatic coast in the Molise region and another on the Tyrrhenian Sea in Lazio. Both projects met with strong opposition. Historian Elisabetta Bini writes that the opponents were "multifaceted and included not only antinuclear movements tied to the far left but also members of the aristocracy (often large landowners) who were part of Italian environmental groups such as Italia Nostra and wanted to defend the landscape, along with their economic interests; and people interested in promoting the expansion of the tourist industry along the coast, following Italians' increased access to paid vacation leave. Farmers also played a crucial role in the debate." In the end, the opponents proved remarkably successful in using their political power to prevent construction of the proposed

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seaside plants.[46] The mythical Italian coast, where the ancient Romans had plunged into the sea and Ulysses and Aeneas had once set sail, thus managed to escape a massive nuclearization. The Latina NPP, a pilot-scale plant completed in 1963, remained Italy's only coastal nuclear power plant.

Spain, too, had a long coastline, in this case facing two seas: the Atlantic and the Mediterranean. Spanish utilities found the Mediterranean shores attractive for cooling purposes, but the tourist industry opposed coastal nuclear construction. In the case of the Irta NPP, which was pre-authorized in 1966, the conflict between the nuclear and tourist industries could only be resolved after a lengthy judicial process. The court eventually ruled that the plant must not be completed.[47] The Vandellòs NPP, by contrast, did materialize, being erected on the Catalan coast 120 km south of Barcelona. Tourist interests did not manage to stop this project. Yet the interaction between the visions of the beach as a tourist destination and as a nuclear site decisively shaped the plant's design. When construction began in 1967, the nuclear engineers were instructed to ensure that the buildings blended with the landscape. The Catalan coast experienced a surge in foreign tourists during these years, so local agencies deemed it critical to maintain the coastline's visual appeal. The quest for "harmony" translated into a camouflage strategy. Leading architects, however, dismissed this idea. Inspired by modernist architectural trends, they argued that the nuclear plant should "reinforce the character of a place and its link to geography." They did not want to simply disguise or hide it. A compromise was eventually reached: The Vandellòs plant was camouflaged on the sides facing the nearby tourist beach, but it was painted a radical red on the opposite side—a color that had no natural counterpart in the coastal landscape.[48]

California's nuclear coast was also the subject of heated debate. Starting in the mid-1950s, atomic proponents argued that the sunny state needed numerous nuclear power plants to cover future electricity needs. They predicted that blackouts would plague Southern California by 1970 unless a series of plants were built along the state's central coast and extending to the Mexican border. They dreamed up futuristic coastal "power parks" that would host eight to ten reactors. Rising grassroots movements effectively opposed these plans by pointing out the area's unknown seismic risks and the sensitivity of the Pacific coast as a liminal environment. From 1972 on, the grassroots movements were supported by the newly formed California Coastal Commission. The opposition was almost as effective as in Italy, and

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all large-scale nuclear projects in California except the San Onofre and the Diablo Canyon plants were eventually abandoned.[49]

The case of Sweden's Ringhals NPP exemplifies how local fishing interests shaped coastal nuclear construction. In the late 1960s, Vattenfall—Sweden's state-owned electric utility—identified the Värö peninsula on the Swedish North Sea coast as a suitable nuclear site. The municipality welcomed the initiative, seeing it as an opportunity to boost local economic development.[50] But the local fishing industry was worried. While not opposing the project as such, they expressed strong views about the proposed cooling water schemes. According to an early proposal, the cooling water would be accessed through a fjord south of the peninsula and subsequently discharged on its northern side. Mobilizing their experiential knowledge of the coastal waters, the fishermen challenged this plan. They argued that a large-scale intake of cooling water from the south would create currents that would pull drifting ice into the passageway used by fishing boats en route to their harbors in the winter. Vattenfall took a conciliatory stance, agreeing to devise a new proposal. They suggested reversing the flow of the cooling water. However, the fishermen objected again, this time more vehemently. They complained that discharging heated cooling water into their fjord would produce unwelcome fog. A nearby fishmeal factory also opposed the design because it required cold process water from the fjord. Eventually, a third, more complex solution was worked out. Two cooling water intake canals would be built on the northern side of the peninsula. The heated cooling water would then be discharged through a complex system of subterranean tunnels stretching 1.5 kilometers, with the tunnels' openings at the peninsula's western tip. Vattenfall agreed to this more expensive solution to keep the fishermen happy.[51]

There was one category of coastal nuclear plants that proved particularly controversial in both Europe and America: those proposed for estuaries. Estuary sites enjoyed the advantages of a seaside location. They also offered logistical advantages in terms of easy access to nearby transportation hubs. But many estuaries were fragile ecosystems and valuable fishing grounds. Others were heavily industrialized, which meant that nuclear builders needed to establish themselves in ways that would not jeopardize the operation of port facilities, factories, and fossil power plants.

The most controversial estuary station in the United States was built at Calvert Cliffs on the western shore of Chesapeake Bay. Critics worried

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about the plant's potential impact on the bay's oyster and crab industries. Echoing the debate over thermal pollution of inland waters, they noted that the proposed reactors would withdraw and return 150 cubic meters of cooling water per second to the estuary. It was feared that this would negatively affect the ecosystem. Many prominent residents of Baltimore and Washington, DC, including a number of scientists from Johns Hopkins University, had summer homes on the bay. This made it easier to bring the issue to the attention of the media and, later, take it to court. The 1971 *Calvert Cliffs Coordinating Council vs. Atomic Energy Commission* case would be remembered as a landmark not only in the history of nuclear energy but in US legal and environmental history more broadly. Among other things, the case established environmental impact assessments (EIAs) as a fundamental principle in industrial planning. In the end, the lawsuit did not prevent the Calvert Cliffs NPP from being built, but it had far-reaching indirect impact on the US nuclear industry because it led to an eighteen-month moratorium on nuclear licensing, significantly slowing nuclear development at a critical juncture.[52]

Meanwhile, on the other side of the Atlantic, West Germany's electric utilities hoped to build numerous nuclear power plants on the shores of the Elbe and Weser estuaries. These tidal reaches were important shipping routes leading to the burgeoning ports of Hamburg and Bremen, and their shores were already heavily industrialized. The utilities argued that the arrival of nuclear power was a natural continuation of these activities. By contrast, opponents viewed the proximity of several large nuclear power plants to industrial and shipping activities as an incredibly dangerous siting strategy. In the case of the Brokdorf NPP, which was to be built on the Lower Elbe, critics argued that an oil or gas tanker passing by the nuclear plant could explode, causing a blast wave that could destroy the station and lead to a nuclear disaster. TÜV Norddeutschland, a licensing body, argued that design improvements were necessary. Meanwhile, the federal minister of transport was concerned that construction of the plant might lead to unnecessary restrictions on maritime shipping. The nuclear builders were asked to provide evidence that the planned nuclear station could withstand "heavy gas explosions."[53] The utilities eventually convinced the licensing bodies that the plant would be safe by promising to make the walls of the containment building 80 cm thick. Permission to build the plant was finally granted in October 1976. By that time, however, antinuclear sentiment in

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Figure 2.6
The Brokdorf nuclear power plant in Germany. The plant was built on the Lower Elbe, an estuary of the North Sea and one of Europe's busiest shipping lanes. The passage of large cargo ships and oil and gas tankers was interpreted as a threat to nuclear safety, necessitating additional investment in the containment structure. *Source*: Photo by the author, November 2021.

the region had grown extremely fierce, and the project became embroiled in conflicts that had little to do with the plant's envirotechnical design.[54] The reactor would eventually be completed, but only after years of heated controversy and violent protests (figure 2.6).

Preparing for the Nuclear Hundred-Year Flood

Nuclear plant builders and operators devoted considerable effort to ensuring that sufficient volumes of cooling water would always be available. The worst-case scenario was that water from the "ultimate heat sink" would become unavailable due to a malfunctioning cooling system or a drought situation. However, the opposite danger also existed: that there might be too much water. The necessity of locating plants close to rivers, lakes, or

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seas made nuclear power disproportionately vulnerable to flooding. Nuclear planners recognized this risk early on and took it seriously, knowing that flooding could endanger critical safety systems. A worst-case scenario was that floodwaters would render the cooling water pumps inoperable, which could cause a core meltdown.

The key technology for preventing flooding of nuclear power plants was thousands of years old. It took the form of dikes and levees—and, if need be, sandbags—designed to protect the plants against rising waters. Constructing a dike was regarded as a straightforward, even banal task. Moreover, nuclear operators could often rely on existing, nonnuclear dike infrastructures. In northern Germany, for example, the Elbe and Weser estuaries were equipped with a system of earthen dikes standing 8.2 meters above normal sea level. The question was how to protect a nuclear power plant against breaches in such dikes. As recently as 1962, the region had experienced a major flood disaster involving numerous dike breaches. A decade later, Nordwestdeutsche Kraftwerke (NWK) began construction of the Unterweser NPP. Recognizing that serious flooding events could occur, the utility asked the Franzius Institute at the Technical University of Hannover for advice on how to cope with such situations. The institute's experts proposed a number of technical fixes. They urged NWK to ensure that all openings and emergency exits in buildings with safety-relevant equipment be placed at least four meters above sea level. One potential flaw in the original plant design was the placement of emergency coolant pumps in the basement of the machine building, but this could be addressed by making sure that they were located in "flood-protected rooms."[55]

The German experts further noted that an oil-fired power plant in the Elbe estuary had survived the 1962 disaster surprisingly well, despite being flooded. The plant was able to resume operations as soon as the floodwaters receded. This was considered an encouraging experience.[56] Yet there was, as always, one fundamental difference between fossil and nuclear power plants: A nuclear station's water pumps had to continue operating at all times, even after a reactor shut down. Failure to do so would lead to the accumulation of decay heat and, in the worst case, a core meltdown.

When preparing for floods, it was important to consider the "economics of safety," or the fundamental tension between risk and cost. For instance, from a risk standpoint, it was evident that nuclear power plants should be constructed at sufficiently high elevations. By contrast, economic

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considerations dictated placing the reactors as close to the water level as possible. "The economic desirability of low pumping head," as one American expert put it, was "obvious," although "flood crests far higher than the predicted maximum have not infrequently confounded the best of prophets."[57] This clash between the two logics led to heated debates. For example, during the planning of the Greifswald NPP in East Germany, flooding concerns prompted East German hydraulic engineers to propose building the plant 10 meters above sea level. Experts from the Soviet Union, who were also involved in designing the plant, argued that 7.5 meters was sufficient. Economic factors aside, they pointed out that the Soviet industry, which would deliver the equipment, would have difficulty manufacturing cooling water pumps powerful enough for the 10-meter level.[58]

Elsewhere, the pursuit of economic efficiency prompted nuclear plant builders to redesign the coastal landscape entirely. This was the case, for example, at EDF's Flamanville site in Normandy, where the rocky coastline with its tall granite cliffs posed engineering challenges. Ideally, the Flamanville plant would have been built on top of the cliffs, high above the English Channel, to minimize risk. However, profitability considerations suggested building the plant closer to the water. Ultimately, EDF decided to remove the cliffs to make room for the plant near the sea. The company was aided by the presence of an old granite quarry, which had already hollowed out part of the cliffside. The extracted granite was used to create a massive platform extending into the sea, on which the nuclear power plant was erected.[59]

The same approach was taken at Fukushima in Japan. Although the topography provided a natural ground level of thirty to thirty-five meters above sea level, Tokyo Electric Power Company (TEPCO), the utility in charge, decided to build the plant at ten meters above sea level to improve its economic parameters. The decision meant that TEPCO had to devote considerable effort to removing "soil and rock layers with a thickness of more than 20 m over a large area." This was a massive undertaking, but it was justified by the cost savings expected during the plant's operating phase due to more convenient access to the Pacific Ocean and its cooling water. The downside was an increased risk of flooding.[60]

Although the engineering community generally agreed that plants needed protection against potentially disastrous floods, the tension between risk minimization and profit maximization meant that planners could not

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account for all conceivable floods. This concerned, in particular, events that were not regarded as "credible" and floods that seemed extremely improbable. To determine which flood risks to address and which to ignore, nuclear engineers examined past floods. Throughout history, hydraulic engineers had discussed flood management in terms of the (un)likelihood of rare events. The most severe floods—including the worst tsunamis—occurred once every century, millennium, or ten thousand years. They were conceptualized as "hundred-year floods" and "thousand-year floods." There was a strong consensus among hydraulic engineers that human societies could not protect themselves against everything. They agreed that a hundred- or thousand-year flood was such a rare phenomenon that the destruction it caused would have to be accepted. Residents in affected regions would certainly be shocked to find their houses and infrastructure destroyed. Restoring them would be costly. However, since this would only happen once every hundred or thousand years, the outcome could be tolerated. Historically, this way of thinking had determined how tall a dike should be, for example, along the Yellow River in China, the Rhine in Germany, the Missouri in America, or the Dutch and Belgian coast in Atlantic Europe.[61] Unsurprisingly, nuclear builders reasoned along similar lines, although they acknowledged that the "potential seriousness of the failure of a nuclear power plant," as one hydraulic engineer put it, necessitated modifications to traditional "frequency analyses."[62]

The US Army Corps of Engineers suggested basing nuclear siting and design decisions on the "probable maximum flood" concept, defined as a hypothetical flood produced by "the most severe *combination* of hydrometeorological and/or seismic parameters reasonably possible for a particular location."[63] The calculations proved more difficult than expected and irritatingly uncertain, however, especially when the task was to assess the probability and combination of events for which there were no historical records. Moreover, while hydrologists emphasized the possibility of very rare, extreme flooding hazards, nuclear plant builders criticized the "probable maximum" approach for being "unduly conservative," as General Electric's nuclear safety experts argued in 1973. "Such conservatism restricts otherwise acceptable sites and is not in the overall public interest." Similarly, Fukushima operator TEPCO, when assessing tsunami risks, did not take into account the possibility of an offshore earthquake with

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a magnitude greater than 9, because that was not considered "a credible event in the Japan Trench."[64]

It may seem inevitable that not all worst-case scenarios were considered in nuclear siting decisions and flood mitigation plans. Not only would construction costs have been exorbitant, but it might have been impossible to find suitable geographical sites, and there might not have been technical equipment advanced enough to address hazards so rare that few could imagine them occurring. Therefore, nuclear plant builders did what their nonnuclear predecessors had always done: They protected their plants against everything except the most severe floods. Just like dike builders in the past, they reasoned that the possibility of an extreme flood—which, in the atomic age, might cause a full-scale nuclear disaster—would have to be accepted.[65] This way of reasoning, inspired by prenuclear flood management practices, would have far-reaching consequences for the fate of the global nuclear industry.

Conclusion

Early nuclear visionaries were preoccupied with inventing reactors of different types and making them commercially viable. When utilities, on that basis, began erecting large-scale nuclear power plants from the 1960s onward, the need for integrating them into local and regional environments added to the engineering challenges. The quest for cooling water supplies was at the forefront, as it was critical to guaranteeing the safety and continuous operation of the nuclear steam engine. Initially considered an easy task, ensuring a continuous and reliable water flow proved to be more difficult than anticipated. Apart from being technically challenging, the marriage of nuclear science with traditional hydraulic engineering grew socially and politically contentious. On inland waterways, the main controversies revolved around thermal pollution and the detrimental effects of cooling towers. At seaside locations, tourism and fisheries were seen to be threatened by nuclear construction. There were also concerns over water scarcity and potentially disastrous flood events. In this way, a whole array of dilemmas at the meso level of nuclear engineering added to the already formidable microlevel challenges, discussed in the previous chapter. It was at the meso level, which exposed nuclear power's intricate

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envirotechnical entanglements, that opposition to nuclear energy—from the side of aquatic scientists, government agencies, and eventually the general public—began to take shape in the years around 1970. A few years later, these controversies would spill over to microlevel conflicts over reactor safety and macrolevel debates about nuclear fuel and radioactive waste. In this context, the envirotechnical dilemmas would temporarily recede into the background, only to resurface with a vengeance in the twenty-first century.

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3 The Quest for a Nuclear Circular Economy

Compared to a nuclear power plant's immense demand for cooling water, its uranium requirements were modest: While a 1,000 MW light-water reactor needed approximately fifty cubic meters (or tons) of water *per second*, it needed only a few hundred tons of uranium *per year*. Refueling occurred only once per year or even less frequently. This was in stark contrast to coal power plants, which required continuous refueling and had an enormous thirst for fuel. The UK's Central Electricity Generating Board, for example, calculated that a large Magnox reactor needed around 220 tons of nuclear fuel per year, while a coal power plant of the same size burned no less than 2.8 million tons of coal over the same period, or about 13,000 times as much.[1] Such comparisons highlighted the nearly incomprehensible energy density of uranium, widely regarded as one of the most attractive features of nuclear fission.

Yet even if the fuel volumes were small, the uranium had to come from somewhere. Suitable ores needed to be found, mined, processed, enriched, and turned into functional fuel elements. Moreover, once the fuel had been irradiated in the reactor, it needed to be safely disposed of or, even better, recycled in advanced reactors, while high- and low-level radioactive wastes needed to be stored in suitable ways for very long periods of time.

This chapter examines how the global nuclear fuel supply system emerged over time. The focus is on the nuclear industry's attempts to align the "nuclear fuel cycle," as the engineers called it, with older extractivist traditions and the ideals of a circular economy. The world's atomic visionaries sought to turn uranium into a commodity like any other. To achieve this, they employed a range of technologies, institutional frameworks, and cultural imaginations that were already well-established in nonnuclear

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contexts. For example, they found it natural to base uranium mining on the same forms of "resource colonialism" that had shaped the global mining enterprise since the sixteenth century. They envisioned the refining of uranium oxides into suitable forms through conversion and enrichment, taking inspiration from iron ore, gold, and petroleum refining. As the term "fuel cycle" suggests, they also tried to "reprocess" spent nuclear fuel, drawing on the long-established ideal of resource recycling so long established in agriculture, the chemical industry, and metals. The history of these fuel-related activities, and the failure to bring about a nuclear circular economy, provide important clues to why nuclear energy did not manage to become a dominant global energy source.

Uranium: Just Another Commodity?

Following the discovery of nuclear fission in 1938–1939 and the realization that a new, radical weapon could be developed based on this principle, military leaders in several countries scrambled to identify uranium deposits suitable for bomb production. Some deposits were already well-known, such as those in St. Joachimsthal (Jáchymov) in what is now the Czech Republic, Shinkolobwe in the Belgian Congo, and Great Bear Lake in northern Canada.[2] Others were discovered through new prospecting and exploration during and after World War II.

The Manhattan Project mainly relied on uranium from non-US sources. However, in the 1950s, vast new domestic deposits were discovered in the red rock deserts of the Colorado Plateau, which were home to the Navajo people. Meanwhile, Britain began extracting uranium from the Witwatersrand gold mines in South Africa and then in Australia, while France searched for uranium in Madagascar, French Equatorial Africa, Gabon, and Niger. The Soviet Union sent geological expeditions to Central Asia and Siberia. Immediately after the war, the Soviets also took control of the Jáchymov mines in Czechoslovakia, as well as the even richer uranium resources in East Germany's Erzgebirge. In China, Communist leader Mao Zedong transformed uranium mining into a popular mass movement with the slogan "The whole people should engage in uranium mining" (*quanmin ban youkuang*).[3]

Since military actors—and others before them—had already invested heavily in uranium extraction, there was no need for civilian atomic

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agencies to set up separate mining ventures. They could tie into what was already there. Following nuclear power's commercial breakthrough in the mid-1960s, many of the uranium mines created for military purposes were expanded, and new mines were opened at nearby locations to meet the increased demand for fuel. Several sites experienced a "second wave" of uranium exploration as civilian nuclear power expanded. This was the case, for example, in the US West,[4] but also in Australia, where several new deposits were discovered. The most significant of these would form the basis for what would become the Ranger uranium mine in the Northern Territory. Meanwhile Canadian uranium mining expanded beyond its origins in Great Bear Lake to other areas.

France, which tested its first atomic bomb in 1960, gradually lost its colonial possessions in Africa, but this did not prevent its nuclear agencies, the CEA and its subsidiary nuclear fuel company COGEMA, from expanding uranium production and starting up new uranium mines in several postcolonial African states, based on agreements with the new governments. Niger's Arlit mine, in particular, which commenced operation in 1971, would play a key role in supplying France's many civilian reactors. By 1974, thanks to its stakes in African mines, France controlled around 15 percent of the world's uranium reserves.[5]

In the Soviet realm, a variety of military mines were extended and new ones started up to meet civilian needs. One notable new project was the massive Priargunsky Mining and Chemical Production Combine in eastern Siberia. A 1968 decision by the USSR Council of Ministers paved the way for it. Located near the town of Krasnokamensk, close to the Chinese and Mongolian borders, Priargunsky would grow to become one of the world's largest uranium mines, helping the Soviets overcome any potential fuel shortages. Meanwhile, uranium extraction increased in Kazakhstan, with multiple mines spread across different parts of this Soviet republic.[6]

Several West and East European countries, including Spain, Portugal, West Germany, Sweden, Bulgaria, and Romania, started up uranium mines. Spain, for example, established two mining ventures near Córdoba and Jáen and a processing plant at Andújar near Seville. West Germany opened a mine in the Black Forest.[7] Most of these uranium mines proved difficult to sustain. One reason was that the United States, in the wake of overproduction of "yellowcake" (powdered uranium concentrate) in the American West and Washington's Atoms for Peace initiative, began to export uranium

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to Europe at favorable prices. Another was that production costs in the European mines were disturbingly high compared to those in the colonies and postcolonial nations, where indigenous mine workers were paid close to nothing. In addition, both the mining and milling of uranium ore came at the price of environmental destruction and health hazards.

The combination of economic and ecological obstacles led a country such as Sweden to favor imported uranium over domestic extraction—despite its vast domestic deposits and rapidly expanding civilian nuclear program. Sweden's pilot-scale Ågesta NPP was the only plant that was ever fueled with Swedish uranium. For all subsequent plants, Sweden's utilities signed import agreements with foreign uranium suppliers such as the Utah Construction and Mining Company in the United States, Eldorado Nuclear in Canada, France's CEA and Uranex (which sourced their uranium from Gabon and Niger), and Rio Tinto Zinc, the international mining conglomerate headquartered in London.[8]

Other nations simply could not find enough uranium domestically. East Asia's rapidly industrializing economies, in particular, lacked sufficient quantities and qualities of domestic uranium. Hence, they were forced to rely on imports. Japan initially bought its uranium from Canada's Denison Mines and exploration ventures in British Columbia and southwest Colorado. It also became very interested in Australian uranium. In 1972, Japan and Australia signed a nuclear cooperation treaty that aimed to enable "direct export of uranium from Australia to Japan for the first time."[9] The Ranger mine's exploitation was closely linked to early contracts anticipating sales to Japanese utilities; the contracts were considered "large enough to justify initial development of the mine." Japanese utilities also signed large-scale uranium deals with Nufcor, South Africa's uranium supplier.[10]

Like Japan, India was deeply troubled by its lack of local uranium resources. This prompted New Delhi to seriously consider a radically different fuel cycle, based on thorium, a radioactive material that was available domestically in the form of monazite sand. The Indian reactors that were actually built, however, ran on uranium, forcing the Indian Department of Atomic Energy (DAE) to conclude import agreements with foreign suppliers. At the same time, Indian geologists searched frantically for domestic uranium deposits. A new Atomic Energy Act, in force from September 1962, opened up aggressive prospecting and exploration in Adivasi (indigenous) lands. This eventually paved the way for the establishment of a uranium

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mining complex at Jaduguda in northeastern India.[11] Even so, uranium scarcity remained a serious problem for India.

Countries that lacked, or did not want to exploit, domestic uranium resources could join foreign uranium ventures. Germany's Uranerzbergbau, for example, partnered with Gulf Minerals in one of Saskatchewan's uranium mines. Spain sought cooperation with Algeria and Brazil. Japan and its nuclear industry forged ties with the CEA and the postcolonial government of Niger to develop that country's Akouta deposit, near the larger Arlit mine, and processing facilities for the ore. Japan's atomic visionaries hoped that this cooperation would help secure a significant portion of its uranium needs. Another French-Japanese venture engaged in uranium prospecting and exploration in Mauritania. Germany and Italy also had stakes in France's Nigerien uranium projects. France itself, besides its large investments in Gabon's and Niger's uranium, held stakes in South African and Canadian mining ventures. Italy tried but failed to acquire a 10 percent stake in Australia's Ranger deposit, but its Agip Mineraria did become active in uranium mining in Canada.[12]

Many of the companies that engaged in uranium mining built on their experience with non-nuclear resource extraction. For example, the Congo's Union Minière du Haut-Katanga, which played a pivotal role in supplying uranium for the first atomic bombs, was originally established as a copper mining venture. South Africa's Nufcor tied into historical gold mining ventures in the Witwatersrand. Rio Tinto Zinc mined a wide variety of base and industrial metals. Starting in the 1960s, a number of oil companies also decided to invest in uranium mining. The oil companies discovered that technologies originally developed for oil prospecting and extraction, such as radioactive well logging and in situ leaching, could be used to enhance uranium recovery. As of the mid-1970s, the oil industry "owned or partly owned 12 of the top 25 uranium mining and milling companies in the US." By 1981, oil companies produced about 45 percent of all uranium in the United States.[13]

Overall, the world's uranium mining enterprises stood firmly on the shoulders of prenuclear extractivist enterprises. As it seemed, uranium mining was not that special. Indeed, once civilian needs became dominant, the nuclear industry expected uranium to become just another commodity, on par with base and precious metals, fossil fuels, timber, and agricultural raw materials. Although nuclear technologies were widely regarded as exceptional due to

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their military potential and high-tech aura, the intuition was to view uranium as an ordinary, even banal material.[14]

However, as the years went by, it became increasingly challenging to maintain this banalization of uranium. As Gabrielle Hecht puts it, uranium "refused to stay ordinary."[15] Harmonizing the supply of nuclear fuel with older extractivist traditions, resource colonialism, and commodity markets proved difficult. In particular, the vision of an international market, which would allow uranium and nuclear fuel in different forms to move smoothly across political borders, proved challenging to sustain. The secrecy practices that the civilian nuclear industry inherited from bomb-makers, the political desire to prevent "unfriendly" nations from accessing uranium, and the fear that a free uranium trade would lead to the proliferation of nuclear weapons clashed with the ideal of an ordinary, transparent marketplace.

Especially after India tested its first nuclear "device" in May 1974—in what Prime Minister Indira Gandhi called a "peaceful nuclear explosion"—fears in the West mounted that an overly relaxed uranium trade posed a serious threat to world peace. Canada had developed a close cooperation with India in nuclear affairs and had delivered the reactor that enabled India to produce plutonium for its bomb. This cooperation, which initially also included nuclear fuel, came to an end as Canada adopted a new, stricter policy regarding both reactor sales and uranium exports. The Canadian government announced that, from now on, all uranium mined in Canada must go toward "peaceful purposes."[16] Apart from tougher safeguards, the Canadians announced that they wanted insight into and control over the entire fuel cycle whenever it was based on Canadian uranium.

The new restrictions made it more difficult not only for India but for all prospective customers to access Canadian uranium. In what followed, failure to reach an agreement with the Canadians created considerable problems for nuclear operators around the world. In 1977, for example, Pakistan was forced to reduce electricity production from its first electricity-generating reactor, the KANUPP station, while it tried to "find an alternative source of the nuclear fuel" it could "no longer get from Canada." At stake was Karachi's electricity supply.[17] Spain was also negatively affected, as were the nine countries that made up the European Economic Community (EEC, the EU's predecessor). Several EEC member states had concluded uranium import agreements with Canada. Their plan was to irradiate Canadian uranium in civilian reactors and then reprocess the spent fuel.

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However, Ottawa hesitated over whether or not to allow European reprocessing of spent fuel containing Canadian uranium, because the plutonium gained in that way could potentially be diverted to nuclear weapon production.[18]

In a similar way, the United States and Australia began tightening their uranium exports. US shipments of uranium to several countries, including West Germany, were severely delayed due to stricter controls. German research and technology minister Hans Matthöfer expressed "surprise and concern" over the NRC's stricter checks. Fourteen German nuclear power plants were "expecting to receive 800 tons of natural uranium and 350 tons of slightly enriched uranium from the U.S." in 1975. Bonn was concerned that the review and revision of NRC regulations might take years, not just a few weeks or months.[19] Brazil's first nuclear power plant, under construction in Angra dos Reis, was also affected. Westinghouse was building it, and the plan was to rely on US nuclear fuel. However, Washington hesitated to allow exports to Brazil. Yugoslavia was another country that found itself in "difficult talks" with the Americans over fuel supply, prompting Josip Broz Tito's regime to consider alternative supplies from France or China for its Krško NPP. In India, meanwhile, the nuclear fuel complex in Hyderabad was reported to be "without fresh uranium feedstock" as of late 1978, pending US uranium export licenses.[20]

Meanwhile, the dominance of colonial and postcolonial regions in uranium mining began to be framed as a problem. Aboriginal groups in Australia's Northern Territory, for example, objected to the government's intention to let private companies start up uranium mining in the Arnhemland Reserve. They were supported by antinuclear groups. The Australian Conservation Foundation urged the government to forbid all uranium exports except for medical purposes. In May 1974, the federal Committee of Inquiry into the National Estate recommended that the Australian government deny export permits in situations where mining would conflict with the "conservation of the national estate." This was found to be the case in the Northern Territory. Moreover, in 1975, the government ordered an inquiry into the environmental effects of developing Australian uranium deposits. While the inquiry was underway, all mining operations came to a halt.[21] Throughout the 1970s and 1980s, uranium mining remained utterly controversial in Australia, with many new mining projects delayed due to anti-uranium protests and skeptical politicians.

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In Africa, Rio Tinto's plans to open the vast new Rössing uranium mine in Namibia (figure 3.1) clashed with South Africa's controversial occupation of that country. In September 1974, the UN Council for Namibia issued a decree prohibiting the extraction and distribution of uranium and other natural resources from Namibian territory. Several countries with ongoing nuclear power programs—including Britain, Japan, Taiwan, West Germany, Spain, and Iran—had signed contracts with Rio Tinto. As access to uranium from the US, Canada, and Australia became more difficult, these countries were counting on Namibian uranium to fuel their reactors. They feared that failure to access Rössing's resources would lead to spiraling nuclear fuel costs and higher electricity prices. Yet, public pressure mounted in Britain and other Western European countries to cancel the contracts.

Protests against uranium imports from Namibia grew louder throughout the 1980s as uranium became "a global symbol of the Namibian liberation struggle." Trading companies attempted to address the situation through "flag swapping," but an increasing number of customers wanted to dissociate themselves from Rio Tinto. In September 1985, the IAEA intervened, demanding that "South Africa stop immediately all illegal mining, utilization, exploitation, and sale of Namibian uranium." In 1986, the United States imposed sanctions. Shortly thereafter, Britain's Transport and General Workers Union called on the UK to cease its imports of Namibian uranium, while Liverpool dockworkers took matters into their own hands by refusing to handle the precious resource. The conflict over Rössing's uranium was only resolved after South Africa belatedly recognized Namibia's independence in December 1988.[22]

By that time, however, nuclear construction had already entered a phase of stagnation worldwide. Earlier expectations that thousands of large reactors would be built had given way to the realization that the atom would contribute much more modestly to global electricity generation. Consequently, the specter of a global scramble for scarce uranium resources receded. Nuclear operators who could navigate the complex web of safeguards and restrictions found themselves in a buyer's market. The potential consequences of import dependence, however, continued to worry countries that pursued nuclear power on a large scale but lacked domestic uranium resources, such as Japan. Furthermore, the challenges India and other Global South countries faced when trying to access the metal on the open

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Figure 3.1
The Rössing open pit uranium mine in Namibia. *Source*: Ikiwaner/Wikimedia Commons.

market served as a reminder that uranium—at least for those who refused to play by the rules established by the great powers—was not a commodity like any other.

Building Enrichment Capacity

In the early days of nuclear energy, many countries aimed to build reactors fueled by "natural" uranium, which contained only 0.7 percent of the fissile isotope U-235. This fuel was used in both the gas-graphite reactors championed by France and Britain and the heavy-water reactors promoted by Canada, Germany, Sweden, and Switzerland. However, the unexpected rise of the light-water reactor as the dominant civilian technology in the mid-1960s changed the outlook. These reactors—whether of the pressurized water (PWR) or boiling water type (BWR)—required uranium with a higher proportion of U-235. The demand for such "enriched" uranium complicated the supply of nuclear fuel. Countries that switched to light-water technology had to accept that the yellowcake they obtained from the mining companies could not be transferred directly to fuel fabrication

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facilities. Instead, it had to undergo a technically demanding and energy-intensive enrichment process and, in preparation for that, conversion into uranium hexafluoride.

Scientists in the United States, the Soviet Union, and Nazi Germany had begun to explore enrichment technologies during and even before World War II. Undoubtedly, the greatest efforts were made in the United States, where uranium enrichment was identified as a promising path toward developing an atomic bomb. Manhattan Project engineers worked on several alternative technologies in parallel, ultimately prioritizing a method referred to as gaseous diffusion. The first large-scale diffusion plant was built at Oak Ridge, Tennessee. Additional facilities were later erected at Paducah, Kentucky, and Portsmouth, Ohio.[23] The Soviet Union, seeking to catch up with the US development during the early Cold War, built a military-oriented enrichment plant at Novouralsk. Britain, France, and China built similar facilities at Capenhurst, Pierrelatte, and Lanzhou, respectively.[24] All of them deployed the gaseous diffusion method.

In 1956, Oak Ridge's K-25 enrichment plant diversified into the civilian realm when it began supplying the AEC's pilot-scale light-water reactors with enriched uranium. A few years later foreign customers were granted access to US enrichment services. The AEC announced that it was "prepared to sell enriched uranium to other nations under 25-year contracts under the same price schedules as are in effect for the U.S. domestic industry."[25] This was perceived as a unique move that contributed decisively to the growing popularity of light-water reactors worldwide in the mid-1960s. Until the mid-1970s the AEC remained the sole provider of commercial enrichment services in the non-communist world, making the commission's facilities an obligatory passage point for all countries without their own enrichment plants who wished to explore light-water reactor technology.[26]

Seeking to break the US monopoly and achieve independence, several West European countries were determined to develop their own enrichment capabilities. The Europeans were particularly interested in centrifuge technology, an alternative enrichment method that seemed to offer a more energy-efficient way of separating isotopes. German scientists and engineers had begun exploring the prospects of uranium centrifuges already during World War II. Three of them—Max Steenbeck, Gernot Zippe, and Rudolf Scheffel—were captured as prisoners of war by the Soviet Union. There, they helped Stalin perfect the technology. In 1956, the three men were allowed

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to return to Germany, bringing their centrifuge expertise with them. Their remarkably simple and elegant centrifuge designs impressed the nuclear engineering community. An alternative enrichment technology, the jet nozzle process, was promoted by scientists at the Karlsruhe Nuclear Research Centre. Thanks to this technological dynamism, West Germany was able to forge ahead with enrichment matters. Britain, the Netherlands, and Italy also pursued research and development on uranium centrifuges.[27]

The Europeans soon concluded that merging their enrichment programs would give them the best chance of competing successfully with the United States. In December 1968, high-level political representatives from Germany, Britain, and the Netherlands met in The Hague to discuss such cooperation. The result was the formation of two international joint ventures that would come to play important roles in European and global enrichment matters, Urenco Ltd. and Centec GmbH. Both focused on centrifuge technology. In the fall of 1977, Urenco took its first two commercial-scale enrichment plants into operation, at Almelo in the Netherlands and Capenhurst in the United Kingdom. A third plant, erected in the German town of Gronau, became operational in 1985.[28]

France initiated a separate international enrichment project. The CEA, with stakes in both military and civilian nuclear technology, considered centrifuges to be an uncertain option in the pursuit of enrichment independence. Instead of investing in this unproven technology, the agency preferred to play it safe and build on its military experience with gaseous diffusion. France invited other European countries to join the venture. Belgium, Italy, and Spain became involved, and what became known as Eurodif was born: an international company devoted to uranium enrichment for civilian needs. Eurodif's Georges Besse gaseous diffusion plant, built next to its military predecessor at Pierrelatte in southern France, was started up in 1979.[29]

The Soviet Union provided its East European satellite states with enriched uranium as part of larger reactor sales packages. Then, in the mid-1970s, Moscow began offering its uranium enrichment services to West European countries as well. In late 1973, Sweden signed a contract with the Soviet nuclear fuel export agency, Tekhsnabeksport, to enrich three hundred tons of uranium. A few months later, Spain's nuclear fuel company ENUSA concluded a similar agreement, paving the way for the Soviets to supply "20% of Spain's demand for enriched uranium for the years 1978 through 1990."

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Other countries that signed Soviet enrichment contracts included Belgium, Italy, and Finland, as well as France and Germany.[30] The Europeans welcomed the Soviet offer at a time when their own enrichment projects had not yet come online and the American plants were struggling to meet their contractual obligations. For Europe's smaller nations, the Soviet option was seen to stimulate competition in the enrichment market and drive down the price. Japan, which had contracts in place with the AEC and Eurodif as early as 1974, was also reportedly interested in Soviet enrichment services. At the same time, Japan was considering a separate multinational venture to secure its enrichment needs: a possible plant to be built in Australia.[31]

Countries in the Global South were also keenly interested in enrichment facilities. In 1975, Brazil struck a widely publicized deal with West Germany for the sale of both reactors and enrichment technology. The latter took the form of the jet nozzle machines promoted by the Karlsruhe Nuclear Research Center. South Africa moved in a similar direction. Its Uranium Enrichment Corporation (UCOR) managed to build its own pilot-scale enrichment facility at Valindaba, 35 km west of Pretoria, based on the jet-nozzle technology. It was started up in 1978.[32] Iran, which embarked on a massive nuclear program in the mid-1970s, took a different path. Rather than building its own enrichment facility, the Shah's government acquired a 10 percent stake in Eurodif and helped finance the Georges Besse plant after Sweden, which had been involved in the early planning of this project, withdrew in 1974. In return, the Iranians were guaranteed access to the facility's output.[33]

In summary, developments up until the mid-1970s indicated an increasing availability of uranium enrichment services. A robust international marketplace seemed to be emerging, characterized by sizeable flows of foreign investment, technology transfer, international trade, and healthy competition among facilities offering commercial enrichment services. Unfortunately, this situation would not last for long. Starting in the second half of the 1970s, uranium enrichment became fraught with tension and conflict, especially regarding the Global South's nuclear ambitions. This was mainly because uranium enrichment facilities could be used to produce weapons-grade material; after all, Manhattan Project engineers had originally developed enrichment technology for that purpose. Especially after India's "peaceful" nuclear explosion in May 1974, the vision of a global, competitive marketplace clashed with concerns about nuclear

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weapon proliferation and the technological ambiguity of uranium enrichment facilities. The United States and Western Europe grew suspicious that civilian nuclear programs in the Global South would be mobilized for military purposes.

That suspicion was not entirely unfounded. South Africa, for example, did have a nuclear weapon program, and the Valindaba enrichment pilot plant, which rested on a diffuse form of cooperation with Germany, became the site where South Africa's Atomic Energy Board produced the highly enriched uranium needed for its six atomic bombs.[34] The Brazilian government had similar ambitions, as evidenced by President Figueiredo's highly secretive approach to enrichment matters beginning in 1978. Frustrated by the difficulty of mastering the jet nozzle technology, military officials pushed for an independent, covert effort to develop centrifuges. Urenco, the leading player in this field, was unwilling to facilitate the transfer of their technology to Brazil. Nevertheless, Brazilian scientists went ahead with pursuing centrifuge development independently, making use of foreign reports detailing the Soviet-German centrifuge developed in the 1950s.[35]

Iraq and Pakistan were two other countries that sought to mobilize centrifuges for military purposes. In both cases, Urenco's machines served as the chief inspiration, casting a dark shadow over this West European company. Overall, in the political and public debate, uranium enrichment was increasingly perceived not so much as a commercially useful technology serving civilian nuclear fuel supply, but rather as an avenue to the bomb. There was a growing consensus in the Western world that uranium enrichment technologies must be closely guarded and that access to Western enrichment facilities should be limited to as few countries as possible. In 1976, the US Congress passed an amendment to the Foreign Assistance Act that "banned economic and military assistance to countries that traded in uranium enrichment technology if they did not comply with IAEA safeguards."[36] Western European governments voiced similar concerns. It did not really matter whether or not a country aimed to acquire nuclear weapons; even when governments merely sought civilian energy independence, the dual nature of uranium enrichment generated suspicion. As a result, it became difficult, in many national settings, to establish a domestic nuclear fuel cycle. In some countries, these circumstances cast doubt on the viability of the atom as an energy source.

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The Rise and Fall of Spent Fuel Reprocessing

The sibling of enrichment was reprocessing. Both were born out of the Manhattan project, and each of them offered a pathway to the bomb. Manhattan scientists had found that weapons-grade plutonium could be produced by radiochemical treatment of spent reactor fuel. After World War II this technology spread to the Soviet Union, Britain, France, India, and China. Several smaller countries were also interested. With the rise of civilian atomic energy, scientists and engineers in the nuclear weapon states set out to mobilize plutonium extraction for commercial purposes as well. The idea was to use fissile plutonium as nuclear fuel in fast reactors, similar to those pioneered by AEC scientists in Idaho in the early 1950s. Moreover, scientists theorized that such reactors could "breed" more plutonium through neutron capture by U-238 atoms. Since 99 percent of natural uranium was U-238, "breeders" could theoretically use this natural resource up to fifty or even a hundred times more efficiently than light-water, gas-graphite, or heavy-water reactors. At a time when the world's uranium resources were perceived as scarce, this seemed like a terrific opportunity to economize on a valuable resource. However, the materialization of this vision hinged on effective spent fuel reprocessing.

The transfer of military reprocessing technology into the commercial realm, the perceived need to economize on uranium, and the dream of breeder reactors coalesced into a wider vision of what nuclear boosters called the (closed) nuclear fuel cycle. This was the nuclear equivalent of an age-old tradition centered on resource recycling and the reuse of waste products. The fuel cycle concept linked up with ideas developed by nineteenth-century thinkers like the German chemist Justus von Liebig, who famously pointed to the utmost importance of "perfecting the cycle of nutrients" in agriculture. This could be achieved by returning the minerals extracted by each harvest to the soil.[37] Another, more immediate source of inspiration was the modern chemical industry's impressive achievement of reusing virtually all waste materials. Indeed, from a fuel cycle perspective, civilian nuclear energy was first and foremost a chemical industry whose purpose was to make optimal use of scarce raw materials.

For the nuclear weapon states, building reprocessing facilities seemed fairly straightforward since the technology—known in the West as the PUREX process—was the same as that used by bomb makers.[38] The AEC

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even planned to use its military plutonium extraction facilities to reprocess civilian spent fuel "until such a time when reprocessing services were available on a commercial basis." Construction of the first US commercial reprocessing plant began in 1963 at West Valley, New York. Becoming operational in 1966, it was run by Nuclear Fuel Services (NFS), a subsidiary of W. R. Grace, a chemical enterprise with roots in the nineteenth-century fertilizer business. By 1972 the facility had reprocessed nearly one thousand spent fuel assemblies. As more and more commercial reactors began splitting atoms in the United States, the demand for reprocessing services increased, spurring the construction of additional facilities. In the early 1970s, General Electric completed the Midwest Fuel Recovery Plant at Morris, Illinois, adjacent to the pioneering Dresden NPP. Meanwhile, Allied General Nuclear Services (AGNS) built a much larger reprocessing plant at Barnwell, South Carolina.[39]

Britain built its first civilian reprocessing plant at Windscale (Sellafield), where a military radiochemical facility, code-named B204, was already in operation. The new plant, B205, was commissioned in 1964. It catered to the nation's gas-cooled Magnox reactors, which had begun generating spent fuel a few years earlier, as well as to the Magnox reactors built in Italy and Japan. The military B204 plant soon ceased reprocessing operations but continued to support the civilian program as a pretreatment plant.[40] The Britons took pride in the fact that B205 recovered 99 percent of the plutonium in spent Magnox reactor fuel. The plutonium was stored for later use in fast breeder reactors.[41] In August 1974, British Nuclear Fuel Ltd. (BNFL), an agency spun off from UKAEA in 1971, announced plans to build another reprocessing plant, dubbed THORP. BNFL planned to take advantage of economies of scale in reprocessing by offering commercial reprocessing services to foreign customers. For this reason, THORP was designed to handle much larger volumes of spent fuel than Britain's domestic reactors produced.[42]

France, meanwhile, built its first full-scale reprocessing plant at La Hague in Normandy. Commissioned in 1966, it allowed for the extraction of plutonium from the country's dual-purpose gas-graphite reactors. The facility, called UP2, was modified in the 1970s to reprocess spent fuel from France's growing fleet of light-water reactors as well as from the nation's pilot-scale fast breeder reactor, Phénix. Like Britain, France also hoped to participate in the international reprocessing business by accepting spent fuel from other

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countries. In this context, the CEA and COGEMA expanded the La Hague plant, paving the way for the new UP3 section.[43]

In the Soviet Union, the Ministry of Medium Machine Building (Sredmash) began erecting a civilian reprocessing facility in the late 1960s. The planning of this plant, dubbed RT-1, coincided with the decommissioning of the country's first military reprocessing facility, Factory B, which had produced the plutonium for the first Soviet atomic bomb back in 1949. The Soviets reasoned that RT-1 could make practical use of Factory B's existing infrastructure. Thus, the civilian reprocessing machinery was installed in the same rooms as its military predecessor. Several deputy ministers and representatives of the nuclear industry protested this decision, regarding the colocation of RT-1 with Factory B as too dangerous and complicated due to the severe radioactive contamination of the buildings and surroundings. Sredmash head Efim Slavsky, however, argued that the RT-1 facility was urgently needed because large volumes of spent fuel from civilian nuclear power plants would soon begin arriving. There was also a demand-side aspect: Sredmash expected to need a lot of plutonium for its emerging fleet of fast breeder reactors. Reprocessing was a crucial task in managing this new nuclear dynamism. The scattered protests thus remained unheard, and, to save time and money, construction of RT-1 began literally on top of its military predecessor. In 1976 Sredmash decided to build another, much larger reprocessing plant. Dubbed RT-2, its construction began at Krasnoyarsk-26 (Zheleznogorsk) in Siberia. Spent fuel from the new Soviet reactor type VVER-1000 would be reprocessed there.[44]

West Germany's reprocessing efforts were led by the Karlsruhe Nuclear Research Centre, where a pilot-scale reprocessing plant was taken into operation in 1971. The plant began by reprocessing spent fuel from the center's own research reactors. It also reprocessed fuel from the West German atomic ship Otto Hahn as well as from three early civilian nuclear power plants: Obrigheim, Stade, and Neckarwestheim. Germany, home to the world's most competitive chemical industry, envisioned a leading role for itself in the "plutonium economy." Under Chancellor Helmut Schmidt, who took office in 1974, the country's major electric utilities and chemical companies initiated a more ambitious, collaborative project: an integrated reprocessing and waste management complex planned at Gorleben in Lower Saxony.[45]

Italy and Sweden were two other European countries with reprocessing ambitions. In 1970, Italy's Committee for Nuclear Energy (CNEN) began

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operating the EUREX pilot reprocessing facility in Saluggia, located in northern Italy. Sweden planned to build a large-scale reprocessing plant at Sannäs on its Atlantic coast for both military and civilian use. The idea was that all Nordic countries would be able to use the plant. Spain and the Netherlands also hoped to build reprocessing plants.[46]

Aside from these national efforts, there were attempts to initiate reprocessing on a European scale. The most significant initiative was launched by the European Nuclear Energy Agency (ENEA), which fell under the Organization for European Economic Cooperation (OEEC, the predecessor of today's OECD). In 1959, its thirteen member states jointly set up the European Company for the Chemical Processing of Irradiated Fuels (Eurochemic). Under the leadership of Erich Pohland, a German chemist with a background from IG Farben, it built a pilot reprocessing plant at Mol, Belgium. It was commissioned in 1966. However, Eurochemic soon found itself competing with various national reprocessing projects, and operations ended prematurely in 1975.[47]

The East Asian countries were equally eager to master reprocessing technology. In Japan, the Power Reactor and Nuclear Fuel Development Corporation (PNC) was granted permission in 1970 to build a pilot-scale reprocessing plant at Tokai on the Pacific coast, based on French technology. The plant was completed in 1974, but test operations did not begin until 1977. By 1984, Japanese nuclear engineers had inserted reprocessed nuclear fuel from the Tokai facility into the Joyo fast breeder reactor, which was built next to the reprocessing plant. This was celebrated as a great achievement because it seemed to create a closed, ostensibly civilian nuclear fuel cycle. In 1980, Japan's leading utilities partnered with a group of industrial actors to build a larger reprocessing facility, again based on French technology. Construction started in the early 1990s at Rokkasho in northern Japan.[48] South Korea and Pakistan were two other Asian countries that negotiated with France for the transfer of reprocessing technology. India and Argentina pursued domestically designed reprocessing projects, albeit on a smaller scale.[49]

Countries without their own reprocessing facilities hoped to send their spent fuel abroad. Numerous international agreements were concluded to facilitate such cross-border shipments. All East European countries that operated Soviet-designed reactors, as well as Finland, whose Loviisa NPP comprised two Soviet reactors, received their fresh reactor fuel from the

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Soviet Union and agreed to send back their spent fuel to the RT-1 facility in the Urals for reprocessing.[50] The Americans offered similar arrangements to countries that purchased their reactors and nuclear fuel from the United States. Especially in the context of reactor sales to "backward" countries in the Global South, the AEC aimed to take back the spent fuel for reprocessing in US radiochemical plants.[51]

In Western Europe, a complex international scheme took form. Countries without domestic reprocessing plants negotiated access to the large British and French facilities, paving the way for an intense cross-border circulation of nuclear materials. Spent fuel "exports" became crucial for many smaller nations but also for larger countries such as Germany and Italy, which were struggling to build their own reprocessing plants but had not yet completed them.[52] The regime eventually extended far beyond Europe, as Japan became a major customer of French and British reprocessing services. In late 1977 and early 1978, Japan's Enrichment and Reprocessing Group (ERG), a body formed by nine regional utilities and the JAEC, signed contracts with France and Britain, respectively, for the reprocessing of 3,200 tons of Japanese spent fuel starting in 1982. These deals enabled the Europeans to finance the construction of their THORP and UP3 reprocessing plants. In the long term, however, Japan aimed to become independent of foreign reprocessing services.[53]

In summary, by the 1970s a near-global nuclear circular economy appeared to be in the making. An impressive number of reprocessing plants were either in operation or under construction in the United States, the Soviet Union, Britain, France, Japan, and a few other nations. Meanwhile, some countries devoted considerable effort to developing fast breeder reactors, which were expected to consume the plutonium produced in the world's reprocessing plants.

However, the marriage between nuclear science and traditional resource recycling ideals proved more difficult to sustain than expected. In the long term, most countries found themselves either unable or unwilling to move forward with reprocessing. There were several reasons for this. First, mastering the reprocessing technology on a commercial scale was more challenging than anticipated. The radioactive pools where the spent fuel was dissolved in nitric acid were not, after all, just another chemical industry. The combination of very high levels of radiation and plutonium's toxicity required extraordinary—and expensive—safety measures. Initially, scientists

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and engineers were optimistic about their ability to cope with these issues, but they soon realized that they had overestimated their capabilities. The US plant at West Valley, for example, "leaked gaseous and liquid wastes in quantities that troubled the AEC," and "workers at the plant received exposures from design flaws and equipment malfunctions." Operations ceased in 1972. Two years later, General Electric decided not to start up its completed reprocessing plant in Illinois because of equipment failures that would require too much work to fix. The project was abandoned, and in September 1974 GE canceled all spent fuel reprocessing contracts it had signed. A group of New England utilities then sued GE, asking $300 million in damages. The third US reprocessing facility, built by AGNS at Barnwell, likewise suffered repeated delays. Eventually, AGNS gave up, and the plant never went online.[54]

The European development was, in the words of *Nucleonics Week*, "as muddled as that in the US." When Britain's B204 pretreatment plant at Windscale, which catered to the B205 reprocessing facility, resumed operation in September 1973 after a period of repairs, "a chemical reaction occurred which released a cloud of radioactive gas." The accident contaminated the entire plant, and thirty-five workers were exposed to radioactive ruthenium-106. BNFL attempted to carry out "extensive modifications" and refurbishments of the pretreatment plant but never managed to put it back into operation. Then, in 1978, the B205 plant suffered another accident, stemming from a buildup of hydrogen gas in a solid waste silo. This resulted in "the discharge of radioactivity through the silo stack for a short period." Consequently, the plant had to be shut down again. In March 1979, another accident occurred, "involving about 10 cubic meters of dilute, highly radioactive waste."[55]

The situation in Japan was hardly more encouraging. The pilot-scale reprocessing plant at Tokai suffered a series of leaks during the testing phase of its operations in 1975, leading to delays. In August 1978, after producing 64 kg of plutonium, the plant was shut down indefinitely due to "piping problems in the nitric acid recovery section." The plant "stopped operation automatically when high-level radioactivity was discovered to be in process steam." It became increasingly clear that the reprocessing needs of Japanese utilities would not be met for decades to come.[56]

Second, reprocessing turned out to be more expensive than expected. The decision to abandon GE's reprocessing plant at Morris, for example, was

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taken on the basis of financial calculations indicating that the facility's technical flaws could be "fixed only at an unacceptable cost."[57] By 1975, *Nucleonics Week* reported that "cost estimates for reprocessing plants are soaring." In France, the expansion of the La Hague facility was originally expected to cost around $100 million. However, it now seemed that the real price tag would be anywhere between $350 million and $600 million. The same trend was seen elsewhere in Europe. As a result, European utilities had "no clear idea how much they [would] have to pay for reprocessing services."[58] In both Europe and America, technical troubles and radioactive leaks led regulatory agencies to impose additional safety requirements, which could only be met through costly new layers of technology and pricier materials.[59] A half-hearted attempt to reopen the old West Valley reprocessing plant, for example, came to nothing following "sharply upgraded NRC seismic design requirements." In September 1976, the owners announced their intention to exit the reprocessing business, because they were "losing millions of dollars every year."[60]

In addition, there seemed to be no real market for the plutonium produced in the world's reprocessing plants. Back in the 1960s, the nuclear industry had assumed that reprocessing would be a profitable business, because the plants would produce valuable fissile plutonium for use in breeder reactors. In 1970, AEC chairman Glenn Seaborg predicted that "plutonium-fueled reactors would provide more than 50 percent of the electricity generation in the United States by the year 2000."[61] Other countries had similar ambitions. In reality, the world's ongoing pilot-scale breeder projects were plagued by endless problems, and a market for plutonium was nowhere in sight, except for the possibility of recycling the stuff in mixed-oxide (MOX) fuel, a blend of uranium and plutonium, in light-water reactors. By early 1975, General Electric concluded that expecting the "back end" of the nuclear fuel cycle to generate profits was "no longer realistic." Spent fuel management had "changed from one of maximizing profitability to one of determining the most economic disposition of spent fuel."[62] In other words, reprocessing was no longer viewed as a source of revenue, but rather as an expensive and cumbersome method for nuclear power plants to get rid of their spent nuclear fuel.

Third, the vision of a global market for plutonium proved unsustainable in the face of fears that the material could be diverted to nuclear weapon production. Concerns escalated quickly after India detonated

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its nuclear device in 1974, which had been assembled using reprocessed spent fuel from an ostensibly civilian reactor. Following the Indian test, Washington launched a diplomatic offensive aimed at ending the reprocessing ambitions—civilian or not—of various countries that might use their plutonium-extraction skills to build bombs.[63] More controversially, President Gerald Ford began to question the reprocessing of spent fuel in the United States itself on proliferation grounds. During the 1976 US election campaign, both Ford and his challenger, Jimmy Carter, declared that they did not support the reprocessing of spent nuclear fuel from civilian reactors. Ford argued that "the United States should no longer regard reprocessing of used nuclear fuel to produce plutonium as a necessary and inevitable step." Carter expressed even greater concern about the nuclear circular economy. In April 1977, the newly elected president announced that he would "defer indefinitely the commercial reprocessing of nuclear spent fuel to (1) minimize the availability of plutonium and (2) reduce the risks of nuclear weapons proliferation."[64]

The US antireprocessing policy caused dismay and perplexity on the international scene. Many developing countries with reprocessing ambitions were frustrated by America's determination to prevent them from achieving a nuclear circular economy. Western Europe's atomic agencies were also unhappy. Although France, Britain, and West Germany all faced technical and economic problems with reprocessing, none of them wanted to follow the US example by simply abandoning their domestic reprocessing programs. They were also angered by Washington's attempts to hinder the export of reprocessing technology to developing countries. The US policy reversal came at the worst possible moment, since France had just begun selling reprocessing facilities to Pakistan and South Korea, while Germany was hoping to export a reprocessing plant to Iran.

Yet by the late 1970s, the Europeans had aligned themselves with the Americans. France agreed to cancel its export contracts. Germany likewise agreed not to export any reprocessing plants. Upset by the French unilateral withdrawal, Pakistan continued its reprocessing ambitions independently. By contrast, South Korea, under pressure from the West, agreed to abandon its vision of a closed nuclear fuel cycle. Taiwan, which had also begun exploring the option of reprocessing, succumbed to US pressure as well. Washington further refused to allow India to reprocess the light-water fuel that the US had supplied to the Tarapur NPP. President Carter eventually

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agreed to accept continued reprocessing of nuclear fuel in Western Europe in exchange for a commitment from Europe to prevent the Global South from acquiring reprocessing technology. Washington also accepted Japan's fuel cycle projects.[65] All other countries were warned not to engage in spent fuel recycling. This was a serious blow to the proponents of a global nuclear circular economy.

For some time, Western analysts speculated that the world's developing countries with nuclear ambitions, together with other nonaligned nations like Yugoslavia, would form "a front against US nuclear policy" and develop closed nuclear fuel cycles on that basis. This possibility was discussed at an international conference on nuclear technology transfer held at Shiraz, Iran, as well as at a meeting of nonaligned countries in New Delhi in 1977.[66] There was also the idea of a possible technical fix, referred to as "coprocessing." This process was designed to yield not pure plutonium but "a mix of uranium and plutonium separable only by a moderately complex chemical operation."[67] Yet this vision of "proliferation-resistant" reprocessing never got off the ground.

Fourth, the nuclear industry faced legal and logistical obstacles to transporting spent nuclear fuel and plutonium over long distances and across national borders. At the outset, the movement of radioactive materials, whether by sea, rail, truck, or air, seemed unproblematic. Until the mid-1970s, for example, spent fuel from research and pilot-scale reactors was regularly shipped across the Atlantic by air.[68] Such transports became controversial over the years, however, due to perceived accident risks and proliferation concerns. In the United States, the Association of American Railroads (AAR) worked with a committee of the Atomic Industrial Forum (AIF) to identify possible accidents that could occur during rail shipments. Many railroads were skeptical of their proposed involvement in spent fuel transports, viewing them as uniquely dangerous. They declared that they would only accept such transports if specially designed trains were offered. This led to conflicts between the nuclear industry and the railroads that had to be settled in court. Furthermore, critics predicted that the emerging US plutonium economy would necessitate security measures that would lead to an unacceptable infringement on civil liberties. Others feared nuclear sabotage, terrorism, or blackmail related to plutonium transport.[69]

The NIMBY syndrome also affected the envisaged shipments of nuclear materials. In 1976, New York City decided to ban shipments of spent fuel,

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plutonium, and highly enriched uranium through its territory. The ban meant, among other things, that Brookhaven National Laboratory could no longer move spent fuel from its research reactors through New York en route to the Savannah River site in South Carolina for disposal. In May 1978, the US Department of Transportation ruled that New York did have the right to ban shipments of radioactive materials through the city. Soon after, several other cities and states banned shipments of spent nuclear fuel through their territories. George Cunningham, the Department of Energy's acting program director for nuclear energy, warned that "transportation could become the limiting factor in maintaining the nuclear option," raising "the specter of some reactors shutting down by 1985 because of insufficient on-site storage of spent fuel and the inability to transport it to waste repositories."[70]

The Soviet Union and its Eastern European allies' spent fuel regime similarly hinged on effective shipments. Formal bilateral and multilateral agreements had to be established for the railbound transfer of spent fuel from reactor sites in Finland and Central Europe to the RT-1 reprocessing plant in the Urals. East Germany faced the greatest challenge in this regard due to its geographical location. Representatives from the East German Ministry of Transport had to sit down with their Soviet counterparts to plan its shipments, but also with their Polish colleagues, who would be responsible for the safe transfer of East German spent fuel through Poland en route to the Urals.[71] The Soviets used specially designed trains for all spent fuel transports, but they had difficulty making these trains available when needed. It was also common for the trains to be damaged en route and require repairs, which exacerbated transport problems.[72]

Spent fuel rail shipments became increasingly controversial in Western Europe, too, culminating in a wave of antinuclear fuel cycle protests in the 1990s. In West Germany antinuclear groups sought to block transportation routes and sometimes physically destroyed railroad tracks. The government was forced to deploy tens of thousands of police officers to ensure the safety of the nuclear shipments. Then, in February 1998, it was revealed that numerous spent fuel casks en route from Germany to La Hague in France were radioactively contaminated on the outside. Angela Merkel, Germany's environment minister at the time, intervened to stop the transports, which did not resume for two years.[73]

All in all, the combination of technical difficulties, radioactive leaks and accidents, cost escalations, the absence of a plutonium market, proliferation

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concerns, and logistical obstacles caused an increasing number of countries to consider reprocessing as a dead end. Instead, the concept of "direct disposal" gained acceptance. This new approach treated spent fuel as nuclear waste, an idea that would have been incomprehensible to nuclear proponents before the mid-1970s. Initially, industry analysts referred to direct disposal derogatorily as a "throwaway nuclear fuel cycle," a term that was only later adjusted to the more neutral "open fuel cycle."[74] By "throwing away" the nuclear fuel, the nuclear industry in the United States and elsewhere abandoned its ambition to marry nuclear science with the ideal of a circular economy. It was a painful decision, but following Carter's antireprocessing policy, one country after another began considering the direct disposal option. Sweden and Finland were among the first to adapt their spent fuel strategies in this direction. Other countries that eventually opted for direct disposal rather than (domestic or foreign) reprocessing were Canada, Spain, South Korea, and Taiwan. West Germany eventually joined as well, after several unsuccessful attempts to build a reprocessing plant. After the Soviet Union collapsed in 1991, several Eastern European countries, including Lithuania, Hungary, Romania, and Slovakia, switched to direct disposal. Slovenia, which inherited the Yugoslav nuclear program, did the same. Elsewhere, governments adopted a wait-and-see strategy, preferring not to decide how to manage their spent fuel in the long term. In the meantime, the fuel was placed in interim storage facilities.[75]

The ideal of a nuclear circular economy survived in only a few countries. Britain continued to promote spent fuel recycling, despite much controversy over BNFL's ambitions. In December 1976, the government called a public inquiry over the proposed THORP reprocessing plant. The facility was eventually approved for construction, but its completion was delayed again and again over the course of the following decades. The expansion of France's La Hague plant proceeded more smoothly. Any public opposition to the project proved toothless. The only question was whether it made economic sense to reprocess French nuclear fuel. Critics claimed that this was not the case and that the La Hague plant was built mainly "to satisfy technological enthusiasts and foreign contracts, not for sound economic reasons."[76]

The Soviet Union and Japan were the only other countries that continued to promote large-scale reprocessing plants. However, it remained unclear in both cases when those plants would be completed, if ever.

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Meanwhile, India continued to pursue reprocessing on a smaller scale. In the twenty-first century, China joined these nations in their efforts to establish a nuclear circular economy.

The Search for the Nuclear Sink

In a true circular economy, there is no waste. All materials are recycled and remain within the system. In the real world, of course, such closed systems do not exist. They are never fully technically feasible, let alone economically viable. This was true of traditional agriculture, which emphasized returning nutrients to the soil, as well as of the modern chemical and metal industries, despite their immense efforts to achieve complete recycling. Any circular system will inevitably have leaks and waste streams. Unsurprisingly, this turned out to be the case in the nuclear industry, too. And in the nuclear industry, waste products that could not be recycled generated problems on a scale not seen in older industries.

Every step in the nuclear fuel cycle generated its own waste products. Uranium mining and milling produced radioactive tailings and wastewaters that flowed into rivers and contaminated aquifers. Uranium enrichment yielded large quantities of "depleted" uranium, consisting primarily of the nonfissile uranium isotope U-238. Nuclear power plants produced spent nuclear fuel, which was sometimes considered a resource and sometimes treated as waste, and radioactive tritium, which was periodically released into local aquatic environments. In addition, each nuclear power plant contained a variety of equipment, machinery, piping systems, and buildings that became radioactive and had to be disposed of when the facility was decommissioned. Reprocessing plants, finally, generated high-level liquid wastes that needed to be contained and stored, along with a continuous stream of low-level radioactive fluids.

Nuclear technologies were widely recognized as exceptional. Even so, the engineering intuition was to view nuclear waste as just another form of industrial waste and to treat it accordingly. In the early days of nuclear engineering, therefore, it seemed harmless to bury large numbers of radioactive waste drums in the ground, dump them in the sea, or continuously discharge liquid radioactive effluent into rivers and coastal waters. After all, humans had disposed of nonnuclear waste in these ways for millennia. While it was recognized early on that radioactivity posed new risks to

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human health, scientists reasoned that these risks were in many ways similar to other health challenges of modern industrial society. They viewed radioactive contamination as the price humans had to pay to enjoy the benefits of a high-technology world. As the chairman of the US National Committee on Radiation Protection, Lauriston Taylor, put it in 1954, "I suspect we shall have to increase our physical toleration to radioactivity when this becomes a real world of atomic production. It may be something like getting used to the fumes of automobiles."[77]

Building on the age-old ideal of resource recycling, nuclear scientists and engineers envisioned how many of the chemical constituents that made up the waste could be separated out and used productively. As *Business Week* speculated in July 1955, just before the first Geneva conference on nuclear energy, "Today's waste may be tomorrow's bonanza."[78] Cesium-137, for example, was regarded as a potentially valuable isotope for industrial radiography, and strontium-90 could be used in storage batteries. In the United States, this spurred the development of methods to remove both cesium and strontium from the liquid waste produced by Hanford's military plutonium plants. Optimists eyed "a growing commercial market for these isotopes." In 1960, a huge demand for strontium-90 by the Space Nuclear Applications Program, which aimed to put the atom to work in rockets, accelerated these efforts.[79] Other radioisotopes found in nuclear waste could conceivably be used "for a variety of medical, industrial, and agricultural purposes." In addition to the fission products, the actinides in the waste, including elements such as americium and curium, were considered valuable resources. The UK's Atomic Energy Authority believed that it might be "possible to use the actinides as fuel in reactors."[80]

In reality, the market for fission products and actinides remained limited, and the vision of eliminating these substances from waste streams was soon abandoned, except for a few purposes such as space exploration. It also became increasingly clear that managing nuclear waste was incomparably more challenging than handling nonnuclear waste. In the case of ocean dumping, for example, marine scientists found that the "dilute and disperse" approach, which had been employed for centuries to render nonnuclear waste products harmless, was ineffective in the case of radioactive materials. As historian Jacob Darwin Hamblin writes, the scientists early on found that "even given sufficient water dilution that would reduce radioactivity to levels acceptable for drinking, there always would be a risk that

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certain minerals or algae in the water would concentrate the radioactive isotopes and present further dangers." Dilution "did not necessarily lead to safety," because radioactive material could "reaccumulate and still pose risks."[81]

Nevertheless, ocean dumping was widely practiced by virtually all countries in the early atomic age. The United States dumped 86,000 containers of radioactive waste into the ocean before abandoning the practice in the early 1960s. Britain dumped much more, and for a longer period of time. By the 1970s, however, growing environmental concerns in Europe and elsewhere were making ocean dumping increasingly contentious. The new zeitgeist was reflected in the 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, which formally ended the dumping of high-level nuclear waste at sea, though Britain and a few other European countries continued to dump low-level wastes in the Atlantic for another decade. Britain's long tradition of sea-dumping finally came to an end in 1983, following growing public and political controversy and radical activism by Greenpeace to stop the practice. Ocean dumping of nuclear waste continued in the Soviet Union, but in 1993 the signatories of the London Convention eventually voted unanimously to formally ban all sea dumping of nuclear waste, including low-level waste.[82]

Coping with liquid wastes was no less problematic than managing the solid and solidified wastes that were dumped at sea. Most of the world's reprocessing facilities, along with many nuclear research centers and uranium mills, built pipelines to conveniently discharge liquid effluent continuously into nearby bodies of water. The UKAEA built pipelines that enabled its bomb-making facilities to release their effluent into the Thames. Liquid waste from the Windscale nuclear complex was discharged into the Irish Sea. France's CEA discharged nuclear waste into rivers such as the Seine and the Rhône. It also built a discharge pipeline at its La Hague spent fuel reprocessing facility that allowed radioactive substances from this plant to be put into the English Channel. Japan built a similar pipeline, 1.8 km in length, to dispose of waste from its pilot-scale Tokai reprocessing facility. The Soviet Union, at its Mayak nuclear complex, turned the Techa River and subsequently the nearby Lake Karachai into radioactive sewers. Waste from Canada's Chalk River nuclear complex found its way into the Ottawa River.[83]

One category of liquid waste was particularly problematic due to its high activity level: the waste stream from reprocessing plants containing the

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fission products. After the world's atomic agencies one by one abandoned the idea of extracting these substances from the waste and selling them as valuable chemicals, scientists began to ponder how to dispose of them. The standard interim solution was to pump high-level liquid waste into underground storage tanks made of steel.[84] In the long term, the main solution was seen to lie in developing vitrification technology, which involved converting the stored liquids into solids by concentrating and containing them in glass or ceramics. Beginning in the 1960s, the United States, Britain, France, Japan, and a few other countries invested considerable sums in perfecting this method. Once vitrified, the waste could be disposed of more easily.[85]

There was only one problem: The canisters containing the highly radioactive vitrified waste had to be stored somewhere. Since the London Convention prohibited the dumping of high-level waste in the ocean, onshore solutions were required. This sparked a search for suitable geological formations that could function as dry nuclear waste repositories. Gaining public acceptance for this method proved challenging. Local communities balked at the prospect of having highly radioactive waste stored in their backyards, knowing it was no ordinary by-product. There was also widespread public dissatisfaction in many countries with the secretive and technocratic approach to waste management that the responsible state agencies inherited from the bomb-makers. And on the technical side, it was not easy to find suitable host rocks that could be proven to be absolutely stable over long periods of time.

The United States initially judged that salt formations would be optimal for storing high-level nuclear waste. Following this approach, the AEC attempted to convert an abandoned salt mine in Lyons, Kansas, into a repository in the 1960s and early 1970s. The project provoked fierce opposition from scientists and from local political leaders from the beginning. Then, it was discovered that the mine was not technically or geologically suitable. This was "an enormous embarrassment for the AEC and a severe setback in the search for a high-level waste repository."[86] The failure to move ahead with high-level waste storage in the United States was repeated later on with the stalled attempt to build a deep geological repository at Yucca Mountain in Nevada.

Many other countries found it equally challenging to advance the search for a nuclear sink. Following fierce local protests, Canada's provincial and

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federal governments issued a moratorium on AECL's search for a suitable waste repository site in 1981.[87] In West Germany, the plans to store the country's high-level vitrified waste from future reprocessing at Gorleben were deemed "technically feasible, but politically impossible" to implement, as Ernst Albrecht, the political leader of Lower Saxony, put it in May 1979.[88] The Dutch government also wanted to investigate the possibility of storing high-level nuclear waste in geological formations, but "regional and local resistance by citizens, societal organisations, companies and politicians eventually obstructed the proposed in situ test drilling." Instead, the Netherlands, along with other countries such as Italy, opted to postpone the search for a solution to the waste problem and, in the meantime, build centralized interim storage facilities.[89]

Progress was more encouraging in France, whose National Radioactive Waste Management Agency (ANDRA), after a number of false starts, managed to begin construction of an underground laboratory at Bure in clay host rock in the 1990s.[90] Even more promising was the development in Sweden, whose nuclear operators joined forces to develop the Kärnbränslesäkerhet (KBS) storage method. The focus was on burying waste in shafts drilled in granite five hundred meters below the ground. Sweden cooperated closely with Finland in this area, and in the long term, these two countries would take the lead in the quest for geological disposal of highly radioactive nuclear waste.[91]

Initially, the smaller nuclearizing countries had hoped to circumvent the waste problem by allowing a foreign agency to reprocess their spent fuel and keep the resulting high-level waste. Beginning in the mid-1970s, however, countries offering reprocessing services required that the waste be returned to the country of origin. In Britain, a *Daily Mirror* article published in October 1975 interpreted BNFL's ongoing negotiations with Japan regarding the reprocessing of Japanese spent fuel as a "plan to make Britain the world's nuclear dustbin." The article stated that "the Japanese want to send us 4,000 tons of lethal waste because their own laws do not allow them to treat it."[92] Public outcry over the plan led to a critical investigation by the House of Commons Select Committee on Science and Technology. The result was a compromise: The British-Japanese cooperation was permitted to continue, but the terms of the contract gave BNFL "the option of returning reprocessing wastes to Japan" after vitrification.[93] From then on, BNFL began adjusting its foreign reprocessing contracts—not just with Japan, but

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with all countries—to require the customers to accept the return of vitrified high-level waste from reprocessing. France adopted a similar policy. The implication was that no matter how small a country's nuclear program was, it could not escape the waste problem by exporting its spent fuel.

Some actors, notably the IAEA, promoted the idea of international waste facilities to relieve the smaller countries of the enormous burden of building their own waste repositories. In a separate move, some smaller West European nations probed the possibility of exporting their spent nuclear fuel to China for reprocessing with no waste return, or to the Middle East or North Africa for burial in remote desert areas.[94] Ultimately, however, nuclear waste nationalism triumphed, and a consensus formed that every country had a moral obligation to deal with its own waste. This discouraged many countries, especially smaller ones that had not yet invested in nuclear power, from doing so. Moreover, a growing number of stakeholders—including many governments—began demanding that no reactor be allowed to go critical unless the responsible utility could demonstrate the safe management of spent nuclear fuel and high-level waste.[95]

The only countries that did not have to worry about domestic high-level waste disposal were the communist countries of Central Europe. They sent their spent fuel back to the Soviet Union for reprocessing at the Mayak facility, and there was no talk about returning the high-level waste. Finland, which built two Soviet-designed reactors, was also included in this scheme. But when TVO, a Finnish nuclear operator, decided to build two reactors of Swedish rather than Soviet design, it had to find an alternative solution.[96]

The decision to abandon spent fuel reprocessing in favor of direct disposal complicated the search for a nuclear sink. One issue was that nonreprocessed spent fuel occupied about nine times the volume of vitrified high-level waste from reprocessing. Another was that the spent fuel contained not only uranium and the fission products but also very large quantities of plutonium. The burial of plutonium in underground repositories created widespread skepticism among an already critical general public. Many scientists thought plutonium was actually not that problematic to handle, but in the public mind the element was inevitably associated with nuclear weapons and deadly dangers. More than any other waste component, plutonium symbolized the Faustian nature of nuclear energy.[97]

Furthermore, the necessity of storing large quantities of plutonium required a reevaluation of the time frames associated with high-level waste

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disposal. In the 1950s, waste management experts considered technical methods that would keep the waste safe for a few decades. For example, when the UKAEA dumped 1,500 tons of nuclear waste off Land's End in 1955, they told the public that the containers "would hold for about thirty years . . . by which time most of the radioactivity inside them would have become harmless."[98] A few years later, H. H. Hess, a Princeton University geology professor, argued that "no system of waste disposal can be considered safe in which the wastes are not completely isolated from all living things for the period during which they are dangerous," which he estimated to be "at least 600 years."[99] By the 1970s, the scientific consensus was that high-level solidified waste from reprocessing would "remain toxic for 1,000 to 10,000 years." With the transition to direct disposal of spent fuel containing large volumes of plutonium, the time frame was extended further. This was because plutonium-239 had an extraordinarily long half-life of twenty-four thousand years. For this reason, the US Court of Appeals ruled that the Environmental Protection Agency (EPA) must "set radiation standards not just for 10,000 years but for one million years."[100] Other countries arrived at similar conclusions.[101] Such a time frame was unprecedented, and it inspired totally new historical and philosophical interpretations of the nuclear waste challenge. There was also the challenge of communicating the danger of nuclear waste to future generations. While scientists and engineers remained confident that the waste storage problem could be solved, critics questioned whether safe storage of nuclear waste was possible under these extreme conditions. The challenge of spent fuel and radioactive waste was increasingly interpreted as an existential threat to the nuclear industry—an "Achilles heel" of the atomic age.[102]

Conclusion

The successful management of the fuel supply chain was a sine qua non for the emergence of nuclear power as a major energy source. The scientific and engineering intuition was to accomplish this by building on already existing, nonnuclear technologies, traditions, and practices. The vision was that the nuclear fuel would become "just another commodity" that would circulate frictionlessly in a variety of physical forms and ever-larger quantities between different corners of the world. Uranium mining did not seem that different from extracting other metals, and unsurprisingly it attracted

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actors already involved in the mining of copper, gold, and zinc. Oil companies, too, entered the uranium business because they found that their prospecting methods could be used profitably to search for nuclear fuel. Uranium enrichment, for its part, was regarded as the nuclear equivalent of petroleum and mineral refining. The nuclear industry also set out to reprocess spent nuclear fuel in order to create a nuclear circular economy. Drawing on the long-established ideal of resource recycling in agriculture and a range of nonnuclear industries, the engineers developed methods to dissolve spent nuclear fuel using standard inorganic chemicals such as nitric acid. The goal was to extract plutonium and other valuable substances and return them to the nuclear fuel cycle.

Yet the marriage between nuclear science and traditional mining technologies, chemical treatment methods, and circular practices became fraught with tension and conflict. As it turned out, uranium could not be treated as just any other commodity, and the vision of a global market in which uranium could circulate freely across borders faced numerous obstacles. Uranium enrichment was, in a similar way, something very different from the refining of oil, zinc, or bauxite. It was difficult to master technically, and there were fears that spreading the technology to the Global South would lead to nuclear proliferation. Only the nuclear weapon states, along with a few other countries—notably the Netherlands, Germany, and Japan—eventually managed to build their own uranium enrichment facilities. All other countries with light-water reactors had to turn to these nations for enrichment services. This created a new form of energy dependence that many governments considered problematic.

Reprocessing, the key stage in the nuclear circular economy, also turned out to be utterly difficult to master. The nuclear industry dreamed up a plutonium economy that would be dynamic and profitable—a centerpiece of global industrial development. Initially, the industry thought it would be able to cope with all technical and regulatory challenges. However, numerous plants that began construction never went into operation due to accidents, cost escalations, environmental and health concerns, fears of nuclear weapon proliferation, and logistical challenges. Meanwhile, the management of nuclear waste faced a deep crisis as it became clear that traditional waste management principles could not be applied to a "nuclear dustbin."

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II Abandoning the Atom: A Drama in Three Acts

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4 From Boom to Crisis

An impressive number of nuclear power plants began construction around the world in the years around 1970, and the general expectation was that the atom would continue to conquer energy markets, enabling nations to progressively phase out fossil fuels. Only a few years later, however, enthusiasm gave way to crisis and stagnation. Nuclear programs were scaled back and numerous planned projects were canceled in North America, Western and Eastern Europe, the Soviet Union, and the Global South. Many plants that were under construction and neared completion were abandoned. Countries that had not yet invested in nuclear power but were considering doing so finally decided against it. Others began discussing the possibility of shutting down existing facilities. Only a few nations, most notably France, went against the trend.

The crisis coincided with the rise of public and political opposition to the atom. The opposition grew increasingly multifaceted as it found new focal points one after another: In the years around 1970 the focus was overwhelmingly on mesolevel problems stemming from nuclear power's envirotechnical entanglements, notably thermal pollution and low-level radioactive discharges. From around 1972 these concerns broadened to encompass microlevel worries over reactor safety and the specter of a major nuclear disaster, caused by design flaws or operational issues with the "nuclear steam engine." After 1975, the debate increasingly incorporated macrolevel issues linked to the nuclear fuel cycle, such as the risk of reprocessing plants becoming tools for nuclear weapon proliferation and the challenge of managing nuclear waste. These concerns, reflecting the three problematic marriages of nuclear science with older technological traditions, added up and created a snowball effect. As a result, by the second

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half of the 1970s, antinuclear sentiment worldwide had reached an unprecedented level of strength.

Yet it would be misleading to claim that public and political opposition to nuclear power *caused* the crisis. To explain nuclear power's downturn, we must examine not only the social and political twists and turns around the atom but also the internal technological and organizational dynamics of the nuclear industry. The attempts to hybridize nuclear engineering with older technological traditions gave nuclear scientists and engineers plenty of headaches. To meet the expectations of regulators, governments, and an increasingly critical general public, they needed to continuously modify the technology and add new layers to it. They built cooling towers and equipped plants with charcoal filters to minimize thermal pollution and radioactive releases. They designed increasingly elaborate emergency core cooling systems to prevent core meltdowns. Stronger materials replaced weaker ones in pipes, valves, and pumps. Reprocessing facilities were progressively adapted to meet new environmental regulations and to prevent plutonium theft. Meanwhile, geologists struggled to find bedrocks that could safely store nuclear waste for up to a million years, and vast sums were invested in developing technologies to solidify high-level liquid radioactive waste. All of this made nuclear power, as a technological system, increasingly complex and expensive. Another worrying trend was that, as more and more nuclear power plants and fuel cycle facilities came online, the number of accidents and incidents began to rise. Such events led to calls for further corrections and improvements. The fixes were often technically effective, but they inevitably added even more to the cost of building and operating nuclear facilities.

The 1979 Three Mile Island accident and the 1986 Chernobyl disaster reinforced this development. These two dramatic events seriously damaged the nuclear social contract—the general public's willingness to accept nuclear energy in return for the promise that it would not cause serious harm. As a result, the already vigorous public and political opposition to nuclear power gained further momentum. Nuclear-industrial actors sought to regain public trust by investing in additional safety arrangements. Once again, however, the corrective actions added to the costs of nuclear power. In an era of low fossil fuel prices, this made nuclear energy less and less attractive.

This chapter traces the evolution of the nuclear industry from boom to crisis. It starts out by surveying the extremely ambitious atomic programs

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that governments, national atomic agencies, and electric utilities presented in the years around 1970. The focus then shifts to the challenge the industry faced in terms of an emerging political debate about reactor safety. This new concern supplemented the earlier criticism of the atom's envirotechnical entanglements discussed in chapter 2. Next, the chapter examines the "everyday lives" of the world's nuclear power plants and the multitude of incidents and accidents that plagued them. Lastly, it discusses how spent fuel and waste management issues became integral to discussions about the future of nuclear power in different national settings.

The Grand Visions

Following the light-water reactor's breakthrough in 1964, utilities across the world rushed to build nuclear power plants to meet rapidly growing electricity demand. At the same time, governments set increasingly ambitious goals for nuclear expansion. It seemed only a matter of time before nuclear power would become the dominant energy source. In light of renewed fears of fossil fuel scarcity, many political leaders and industry analysts concluded that there was simply no alternative.

Britain had earlier been the leading country in terms of civilian nuclear investment, but from the mid-1960s onward, the United States assumed global leadership. The years around 1970 saw frantic activity in terms of new reactor orders and construction starts across America, with dozens of new rectors initiated each year. In 1972, no fewer than thirty-five new reactor sales were announced nationwide, a number that rose to forty-four in 1973, an all-time high. Nuclear power, so it seemed, was well on its way to becoming the nation's dominant energy source. Washington expected that the United States would have a thousand large-scale reactors in operation by the year 2000. The onset of the 1973–1974 oil crisis seemed to further confirm the need for massive nuclear investment. The atom played a pivotal role in President Nixon's "Project Independence," launched in November 1973 in response to the Arab oil embargo. Nixon envisioned nuclear energy covering 50 percent of total US electricity demand by 2000, with breeder reactors playing an important part in achieving this goal. The plan was to have four hundred fast breeders in operation by the end of the century.[1]

Neighboring Canada's atomic visionaries were no less enthusiastic. Based on its Douglas Point pilot-scale reactor, which went critical in

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November 1966, Ontario Hydro set out to build its first commercial CANDU stations. By 1973, the utility had taken into operation no fewer than four 500 MW reactor blocks at the Pickering site on the shores of Lake Ontario and, by 1979, four larger, 750 MW units at Bruce on Lake Huron. From 1974, Ontario Hydro expanded the Pickering station by building four additional CANDU reactors. Then, from 1978, another four were added to the Bruce NPP. Meanwhile Hydro Quebec took its pilot-scale 250 MW Gentilly-1 reactor into operation in 1972 and then started construction of the larger Gentilly-2 unit. In the Maritimes, the New Brunswick Electric Power Commission began erecting a 600 MW CANDU reactor at Point Lepreau, twenty miles southwest of Saint John.[2]

Canadian utilities hoped to build numerous additional nuclear power plants to meet escalating electricity demand. In Quebec it was expected that "the bulk of new generation will be nuclear-electric" following completion of the James Bay hydroelectric stations, because "by that time nuclear power should be more economic than the even more remote hydro-electric resources then available." In the Maritimes, AECL deemed it "reasonable to expect nuclear power to provide much of the new generating capacity." In the West, Manitoba Hydro planned to build several nuclear stations, aiming for "a phased transition from the hydro-electric to the nuclear-electric era." It was expected that other provinces would follow suit and that "before the end of the century all provinces of Canada" would be "relying on nuclear power to a greater or lesser degree for their electrical energy."[3]

On the other side of the Atlantic, Britain's Central Electricity Generating Board (CEGB) and the South of Scotland Electricity Board (SSEB) had commissioned nine nuclear power plants by 1972, each comprising two reactors of the Magnox type. The two state utilities aimed to further expand the role of nuclear power in the British electricity system based on an updated reactor model, the advanced gas-cooled reactor (AGR). In early 1973, the CEGB announced that it planned to order no less than 55,000 MW of new electrical capacity by the end of the 1980s, most of which was expected to be nuclear. After the 1973–1974 oil crisis, the envisaged role of nuclear power grew even more. In 1976, the UK Atomic Energy Authority forecast that the UK would have 104,000 MW of installed nuclear capacity by 2000 and an astonishing 426,000 MW by 2030.[4]

Continental Western Europe was a few years behind Britain and the United States in civilian nuclear construction, but many countries dreamed

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of a radiant future. By the early 1970s, a significant number of reactors were under construction or already operating, and it was widely expected that nuclear power would become the most important source of energy across the continent. In March 1974, the French government presented the Messmer Plan, a new nuclear expansion strategy aimed at constructing one hundred reactors at forty sites by the year 2000.[5] Germany, not to be left behind, planned to add 50,000 MW of nuclear capacity, corresponding to fifty large 1,000 MW reactors, by 1985.[6] In December 1975, the Italian government approved a National Energy Plan with nuclear energy at its core. The plan called for the completion of twenty reactors within a decade, which would cover 70 percent of Italy's future electricity needs.[7] The Swedish electricity industry aimed to build twenty-four large reactors. In cooperation with municipal actors, it also considered erecting thirty-five small nuclear stations for district heating systems, "thus saving the oil now used for this purpose."[8] Spain, Switzerland, Finland, Austria, Belgium, and the Netherlands were also busy building nuclear power plants in the early 1970s, and all of them intended to accelerate nuclear investment in the years to come.[9]

Other West European countries had not yet built any large-scale nuclear stations but hoped to do so in the near future. Denmark's ELSAM utility announced in early 1974 that it was about to seek turnkey nuclear bids "for a 1,000 MW plant to be operational by 1980." Inspired by Sweden, Denmark's Ministry of Housing further suggested that nuclear plants could replace oil-fired stations in the country's district heating systems.[10] In February 1972, Norway's National Power Board announced that it would "call for bids in about a year" on its first nuclear station, with the goal of having it operational by 1980.[11] Ireland eyed Carnsore Point, on the southeastern coast, as the ideal site for its first nuclear power plant. The republic's Electricity Supply Board was so optimistic about nuclear energy that it signed a ten-year uranium enrichment contract with Urenco to supply fuel for the planned plant.[12] Portugal aimed to have its first reactor online by 1978. The government announced that "after 1980 all new power demand will be met by nuclear units and that by the year 2000 Portugal will have 7,000 MW of installed nuclear capacity."[13] Greece drew up an ambitious plan to build no fewer than fourteen nuclear power plants by the end of the century, with the first to be constructed on the island of Evia.[14] Even Luxembourg, its tiny size notwithstanding,

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initiated a feasibility study for a 1,200 MW nuclear station, to be erected on the Moselle River in partnership with Germany's largest utility, RWE. A jointly owned company, Société Luxembourgoise d'Energie Nucléaire, was set up for this purpose.[15]

On the other side of the Iron Curtain, the Soviet Union launched a major effort to build multiple large-scale nuclear power plants based on two reactor models: the VVER-440 pressurized water reactor and the RBMK-1000 graphite-moderated, water-cooled reactor. The first VVER-440 reactor, installed at Novovoronezh in southern Russia, began commercial operation in 1972, and in the following years nine additional reactors of the same type went online at this site and high up on the Arctic Kola peninsula, deep down south in the Armenian republic, and at Rivne in western Ukraine. Meanwhile four RBMK plants, each comprising four reactors, were built at Leningrad, Chernobyl, Smolensk, and Kursk. A fifth station, comprising several reactors of the larger RBMK-1500 type, began construction at Ignalina in Lithuania. Moscow also initiated a significant export campaign, selling VVER-440 reactors to East Germany, Bulgaria, Czechoslovakia, Hungary, and Finland. Light water reactors aside, the Soviets invested in fast breeders. A first large-scale breeder reactor, the BN-350, was built at Shevchenko (Aqtau) in Kazakhstan.[16]

The Soviet plans grew bolder in the course of the 1970s as the nuclear industry gained more momentum and political support. The 1980–1985 and 1985–1990 five-year plans were extremely ambitious. The goal was to install 67,000 MW of reactor capacity during the 1980s and 100,000 MW by 1993.[17] The planners envisaged nuclear colonization of regions such as the Volga-Urals area and southern Ukraine, including a plant on the Crimean peninsula. The new VVER-1000 reactor type was identified as the most important vehicle for expansion. It was a significantly improved version of the VVER-440, in terms of both its greater power output and its safety features. With their airtight containment structures, VVER-1000 units could be built close to major cities—a feature that was particularly appreciated in densely populated regions.[18] The new reactor also inspired efforts to build "dual-use" nuclear plants, which would produce both electricity and heat, near cities such as Minsk, Kharkiv, and Odessa. Another intriguing Soviet development line centered on the AST-500 reactor. Optimized for use in district heating systems, it was seen as a means of conserving fossil fuel resources. Both the Soviet Union and its communist satellites had high

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hopes for the AST-500. The East Germans hoped to use it to provide process heat for its sprawling chemical industry.[19]

The East Asian countries, most of which lacked domestic fossil fuel resources, saw nuclear investment as a way to end their chronic energy shortages. Japan aimed to master all facets of nuclear engineering early on. After completing the country's only Magnox station in Tokai in 1966, Japan's atomic agencies, utilities, and equipment manufacturers began working closely with General Electric and Westinghouse to transfer American pressurized water reactor (PWR) and boiling water reactor (BWR) technology to Japan. The first Japanese BWR plants began operating in 1970–1971: one at Tsuruga on the Sea of Japan and another at Fukushima on the Pacific coast. Meanwhile, a PWR station was built at Mihama, not far from Tsuruga.

TEPCO, Kansai Electric Power (KEPCO), and other Japanese utilities proceeded to build many more plants. Hitachi, Toshiba, and Mitsubishi, meanwhile, successfully appropriated US nuclear technologies and gradually took over plant design and construction responsibilities from GE and Westinghouse.[20] By 1968, Japanese firms had already "demonstrated a capability in the manufacture of nuclear steam supply systems." Hitachi, Japan's leading steam turbine maker, was even said to be "actively bidding on projects in the United States."[21] In terms of domestic expansion plans, the Japan Atomic Industrial Forum (JAIF) confidently predicted in 1971 that the country would have 220,000 MW of nuclear capacity online by the year 2000, the equivalent of 220 large 1,000 MW reactors. A total of 27,000 MW of this capacity would be installed by 1980. In the long term, light-water reactors were expected to give way to fast breeders.[22]

Neighboring South Korea's authoritarian government made the formal decision to invest in large-scale nuclear power plants in 1968. Construction of the republic's first station, which relied on Westinghouse PWR technology, began at Kori, near Busan, in 1971. In June 1974, the government published a plan to install 6,600 MW of nuclear generating capacity by 1986. Its ambitions grew in the following years. In January 1978, the government announced its intention to support the construction of as many as forty-six large reactors by the year 2000.[23] The Korean military dictatorship also struck a partnership with Canada's AECL. This resulted in the start of construction of a CANDU reactor at Wolsong in 1977. Meanwhile, construction of two French-designed PWRs began at Hanul in 1983. In the

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longer term, South Korea aimed to become technologically independent in the nuclear field.[24]

In Taiwan, US engineering consultants and IAEA experts helped develop an ambitious nuclear program that included plans for twenty reactors at four coastal sites. Construction of the first two reactors, at Chinshan, started in 1972–1973. Two more stations were initiated at Kuosheng and Maanshan in 1975 and 1978, respectively. A fourth Taiwanese plant, to be built at Lungmen, was approved by the government in 1980.[25]

Further south in the Asia-Pacific Region, Australia and New Zealand were considering nuclear power as a future source of electricity, anticipating that it would become cheaper than fossil power. In 1968, the Australian government approved the idea of building a nuclear power station at Jervis Bay on the south coast of New South Wales.[26] A request for bids for the plant was issued in 1971, and several foreign suppliers responded. New Zealand, for its part, relied mainly on hydropower for its electricity supply, but growing electricity consumption prompted the government to consider nuclear energy as an additional power source. The 1968 annual report of the New Zealand Electricity Department (NZED) recommended a 250 MW reactor to start operation in 1977, "with three similar units following at yearly intervals." Those reactors, it was believed, could conveniently supply 80 percent of Auckland's electricity by 1990. Following the first oil price shock of 1973–1974, NZED again argued that "plans for introducing nuclear power must be made" and proposed building two 600 MW reactors, to become operational by 1988.[27]

Lastly, many countries in the Global South dreamed of nuclear power as a pathway to industrial strength and economic prosperity. The governments of India, Brazil, and Iran were the most ambitious, aiming to construct dozens of medium- and large-sized reactors. India's first two nuclear plants, the Tarapur and Rajasthan NPPs, were built in cooperation with the United States and Canada. With Canadian help, the Department of Atomic Energy (DAE) then set out to erect the Kalpakkam NPP, with two 200 MW heavy-water reactors near Madras. In June 1972, the Indian government approved the country's fourth nuclear power plant, comprising similar reactors, at Narora on the Ganges River in the northern province of Uttar Pradesh. As of 1975, when cooperation with the North Americans was already being phased out following India's 1974 nuclear explosion, New Delhi's goal was to have 6,000–8,000 MW of nuclear power capacity by 1990 according to

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a DAE plan that called for the completion of thirty reactors at fifteen sites. Meanwhile, an experimental fast breeder reactor began construction at the Kalpakkam nuclear research center. It was part of a broader vision for an Indian nuclear circular economy, in which the DAE aimed to master the entire nuclear fuel cycle.[28]

After some hesitation in the 1960s, Brazil also decided to "go nuclear." In May 1971, the country's Central Electrica de Frunas utility picked Westinghouse to supply its first commercial reactor, a 600 MW unit to be built at Angra dos Reis, on the Atlantic coast, about sixty miles south of Rio de Janeiro.[29] Three months later, the National Nuclear Energy Commission announced plans to build multiple 1,000 MW units "to be brought on stream at a rate of one a year from 1977 to 1990." Over the next few years, the expectations continued to grow. By 1974, Brazil was reported to be "gearing up to go nuclear in a big way," aiming to have a whopping 60,000–70,000 MW of nuclear capacity online by the end of the century.[30] A breakthrough seemed to materialize in June 1975, when the government signed a massive nuclear cooperation deal with West Germany, under which Brazil would buy at least eight 1,200 MW German-made PWRs. Construction of the first of these reactors began in 1976, right next to the Westinghouse station at Angra dos Reis.[31]

Following the 1973–1974 oil price shock, Iran embarked on a spectacular nuclear power program that rivaled Brazil's. The Shah signed letters of intent with Germany's Kraftwerk Union (KWU) for two 1,240 MW units for 1980 and 1981 delivery and with France's Framatome for two 900 MW units for 1982 and 1983. The country's long-term goal was to have no less than 23,000 MW of nuclear capacity in operation by the early 1990s. In August 1975, the Germans arrived at the Bushehr site on the Persian Gulf, where they began to erect Iran's first nuclear power plant. The French began constructing their first Iranian plant on the east bank of the Karun River, 45 km north of Abadan, in late 1977.[32]

A few other "southern" countries aimed to make nuclear power a dominant source of electricity as soon as possible. In 1976, for example, the government of Pakistan announced plans to acquire twenty-four large reactors by the year 2000. Argentina, which commissioned a 317 MW Siemens heavy-water reactor as early as 1974, similarly planned to expand its nuclear generating capacity on a massive scale to 10,000 MW by 2000. Mexico's Federal Electricity Commission tentatively advanced a plan in

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1975 to build "twelve to fifteen nuclear plants in the thousand-megawatt range" by the mid-1990s. Construction of the first reactor started a year later at Laguna Verde on the shores of the Gulf of Mexico. Meanwhile, the Philippines, under President Ferdinand Marcos, began construction of the Bataan NPP on the South China Sea in 1976. The country's overall nuclear program was expected to bring nearly 4,000 MW of nuclear capacity online by the year 2000.[33]

Elsewhere in the Global South, the visions were less grandiose. Even so, nearly every government worked hard to initiate construction of at least one full-scale nuclear power plant. The Pinochet military dictatorship in Chile, for example, was reported to be seeking bids for site studies connected with a proposed 600 MW nuclear plant in 1977.[34] Cuba's communist regime cooperated with the Soviet Union on two 417 MW reactors at Juragua in the province of Cienfuegos. Fidel Castro put his son, who had studied nuclear physics in Moscow, in charge of the project.[35] In the Middle East, Ba'athist Iraq began negotiating with Italy for a 640 MW pressurized-water reactor, while Egypt under Anwar Sadat hoped to construct a similar-sized reactor at Sidi Kreer, west of Alexandria, with the help of the United States. France and Germany also hoped to sell reactors to Egypt. In the case of neighboring Libya, French Premier Jacques Chirac's visit to Tripoli in 1976 led to a preliminary deal that would provide Muamar Gaddafi's radical regime with "a nuclear plant for water desalting in addition to electricity production." Algeria and Tunisia, meanwhile, were reportedly "considering a joint nuclear power plant of about 600 MW to be operated by the respective state utilities." Israel and Turkey likewise hoped to build nuclear power plants on their Mediterranean shores.[36]

In Southeast Asia, the Thai cabinet approved construction of the country's first nuclear power station in 1971, to be built in the province of Chonburi, near Bangkok. Indonesia considered a 600 MW nuclear plant for 1983 operation to meet escalating electricity demand on Java. Even Bangladesh, one of the world's poorest countries, reportedly "commissioned the French to do a feasibility study on building a 125-MW nuclear power unit," for which a suitable location had been spotted at Rooppur, a hundred miles from Dhaka. France also studied "the possibility of two nuclear power units for New Caledonia" to power its sprawling nickel industry. There was even talk of a possible nuclear power station for the island of Tahiti in French Polynesia.[37] In essence, there was hardly any region on the planet where

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governments, planners, and utilities did not recognize nuclear power as a viable energy source.

The Politicization of Reactor Safety Concerns

Very few of the grand visions for nuclear expansion that were formulated in the 1960s and 1970s would ever materialize. Nuclear power never became a dominant energy source except in a handful of countries, and the last few decades of the twentieth century did not become the golden atomic age that nuclear boosters had dreamed of. In most countries, governments and utilities eventually backed away from their ambitious plans. Elsewhere, the expansion stagnated within a few years. In the end, most countries in the world never built a single nuclear power plant.

The first signs of what was to come already appeared in the late 1960s in North America and Western Europe. As discussed in chapter 2, large-scale nuclear power plants came under scrutiny around that time as critics voiced their concerns about the envirotechnical entanglements of these machines. This sparked a vivid debate about thermal pollution and other potentially destructive impacts of nuclear power on wet ecosystems. In the early 1970s the problem of continuous radioactive releases added to these mesolevel fears. In the United States, the newly founded Environmental Protection Agency (EPA), along with state-level pollution control agencies, pressured electric utilities to install technologies that would minimize both thermal and radioactive discharges. Concerned scientists, environmental organizations, public interest law firms, ad hoc local groups, and individual citizen activists pushed the nuclear industry further, trying to halt construction or at least force nuclear builders to modify their plants. The critics closely monitored the AEC's licensing of new nuclear power plants and intervened in numerous court cases involving site-specific environmental issues. They were often successful, and in many instances, utilities withdrew from sites deemed too environmentally sensitive. In other cases, construction was contingent on changes—often expensive ones—to the plant design. By 1972, utilities and reactor vendors were becoming increasingly desperate about the sheer number of environmental requirements they had to comply with due to court rulings. They were also disturbed by the licensing delays that resulted from complex court cases and in-depth hearings regarding specific nuclear plants and their environmental impact.[38]

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In the meantime, another challenge entered the public realm: reactor safety. As discussed in chapter 1, nuclear scientists and engineers began discussing this issue internally in the 1950s and 1960s, and the topic gained more attention as nuclear reactors grew larger. It was widely recognized in the expert community that large-scale nuclear power plants were problematic from a safety point of view. Yet, the engineers were optimistic that they would be able to address all safety concerns in due time. Inspired by an enthusiastic scientific and technological zeitgeist, in this age of spaceflight, the experts anticipated the coming of elegant solutions to dilemmas such as the "China syndrome." It was this mentality that led the AEC to approve construction of dozens of large nuclear power plants in the late 1960s, even though the commission's experts knew that the technology was not yet mature. Gradually, it became clear that the challenges would not be that easy to overcome. The "taming" of the nuclear steam engine would not, after all, be that straightforward. A number of unexpected difficulties arose.

In particular, the engineers struggled to develop reliable emergency core cooling systems (ECCS). These systems were critical for preventing nuclear disasters in large reactors. The reactor vendors claimed that their nuclear steam engines were safe and that they were taking a "conservative" approach to safety in the context of ECCS, leaving large safety margins. However, engineers at the Idaho National Reactor Testing Station voiced concerns. In the early 1970s, they conducted experiments with the ECCS offered by the reactor vendors, and the results were not that encouraging. The engineers warned the AEC not to rely on "illusory margins of safety." This sparked a major internal controversy within the AEC. Some scientists and engineers were extremely critical. In an internal memo, they pointed out that a range of studies of large-scale nuclear power reactors "served to raise serious questions regarding the basis for reasonable assurance concerning the operation of these complicated systems." Despite this critique, in June 1971, the AEC ultimately opted to approve the ECCS designs proposed by Westinghouse, General Electric, and other reactor vendors.[39]

The hint that ECCS might be ineffective and that reactors might not be "safe enough" soon became a powerful new argument for opponents of new nuclear power plants across the United States, whose focus, up to that point, had been on the envirotechnical entanglements at specific sites. By late 1971, public questioning of ECCS adequacy was omnipresent. Reactor safety was increasingly added to the agenda of local licensing hearings

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and court cases concerning specific plants. In response to growing public concern, the AEC decided to hold formal hearings on its approved ECCS designs starting in January 1972. Dozens of environmental and public interest groups decided to participate. The hearings, which continued for nearly two years, brought the safety issues of nuclear energy to the forefront. Pressure mounted on the AEC to impose stricter ECCS criteria. By the mid-1970s, new ECCS rules forced utilities and reactor vendors to modify their systems, both in future plants and in operational stations through costly retrofits.[40]

The case of Sweden illustrates how the US reactor safety debate spread to Europe. Sweden was home to multiple environmental organizations, including the Swedish Society for Nature Conservation (Naturskyddsföreningen), the Environmental Center (Miljöcentrum), and the Swedish branch of the Friends of the Earth, along with a number of nongovernmental organizations (NGOs) that opposed nuclear weapons. These groups launched a massive critique of the nuclear steam engine. They closely followed the American safety debate that began in earnest in 1972 and published numerous articles about the controversies on the other side of the Atlantic in Swedish newspapers. Several antinuclear books from the United States were translated into Swedish. This sparked a vivid public debate centered on intricate technical issues, such as the reliability of cooling-water pumps, valves, and emergency core cooling systems, as well as hypothetical disaster risks.[41] The criticism was taken seriously, especially since the Swedish physicist and Nobel laureate Hannes Alfvén—who had previously been actively involved in Swedish nuclear planning—became a vehement opponent of nuclear energy, persistently pointing out the immense risks associated with the nuclear steam engine. Meanwhile, the Environmental Center invited renowned US antinuclear experts, such as Arthur Tamplin and Henry Kendall, to participate in antinuclear activities in Sweden, including a major symposium on nuclear safety held in Stockholm in March 1975. Ralph Nader, a key leader in the US antinuclear movement, later joined them, participating in a Swedish antinuclear event in February 1976.[42] Eager not to alienate its voters, the ruling Social Democratic Party responded flexibly to the shifting zeitgeist. In 1974, Prime Minister Olof Palme called for "a period of reflection," during which the public was encouraged to actively engage with the technical as well as the social aspects of nuclear power in a democratic society.[43]

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There were reactor safety debates elsewhere in Western Europe, too. The German safety discourse emerged from the observation that West Germany was much more densely populated than the United States. The implication was that German safety requirements would have to be more stringent. A central dilemma was the difficulty of finding suitable West German sites that were not near major cities. In 1969 the chemical company BASF confidently applied for a construction permit to build a large nuclear power plant in the center of Ludwigshafen, a major industrial city. The specter of a possible nuclear disaster that might wipe out an entire city alerted regulators. The proposal to build "the world's most powerful nuclear reactor" at Biblis, not far from Ludwigshafen, sparked further debate. The light-water reactor models that were promoted in Germany were essentially American designs built by Germany's Kraftwerk Union (KWU), a subsidiary of Siemens and AEG, under licenses from Westinghouse and General Electric. Accordingly, when the US reactor safety controversy emerged in 1971–1972, it raised doubts about the reliability of KWU's safety technologies. As critics proposed a series of new, costly safety measures that conflicted with the economic interests of manufacturers and electric utilities, the German nuclear industry grew increasingly nervous.[44]

In the BASF case, regulators eventually issued a construction permit, but only under the condition that the reactor be equipped with a burst-proof containment "in case the reactor pressure vessel should blow up"—an event that officials regarded as credible in Germany but not in the United States.[45] This decision would have far-reaching consequences for Germany's nuclear future. Upon learning about the novel, safer design, the opponents of the Wyhl NPP further upstream on the Rhine demanded that "their" nuclear reactor be equipped with the same safeguards. The rural population in the area argued that they were entitled to the same protection as people in big cities, and the courts agreed. The judges conceded that a rupture of the reactor pressure vessel was only a very remote possibility. However, if it did happen, steel fragments could crack the outer containment, leading to radioactive releases into the atmosphere. Such an accident would have enormous consequences, representing a "national catastrophe." Consequently, in March 1977 the Freiburg Administrative Court nullified the construction permit that had been granted two years earlier for the Wyhl NPP. This was a remarkable victory for the German antinuclear movement, and it inspired a wave of further antinuclear activism. A KWU source

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prophetically commented that the Wyhl decision "could be the beginning of the end of nuclear power in Germany."[46]

Britain's nuclear scientists and engineers emphasized that certain reactor types were safer than others. They were skeptical of the American light-water reactors, considering them to be inherently dangerous. The reports from the ECCS hearings in the United States seemed to confirm this conclusion. The British nuclear program was based not on light-water technology but on the gas-cooled Magnox and AGR reactor types, which were essentially spinoffs of the military's plutonium-producing machines. The Magnoxes and AGRs were considered safer than PWRs and BWRs, because their pressure vessels were larger, featured lower power densities, and were made of reinforced concrete rather than steel. This was thought to safeguard Britain's nuclear power plants against the traditional risk of a steam explosion. The drawback was that the gas-graphite reactors were more expensive. For this reason, much of the debate about nuclear energy in Britain revolved more around cost management than safety.[47]

The economic advantages of light-water reactors, as well as the perceived risks associated with them, would continue to haunt Britain throughout the 1970s. In 1972 a major debate erupted around the choice of reactor for the nation's third nuclear program. CEGB, which was primarily interested in producing electricity as cheaply as possible, pointed to the superior economics of light-water reactors. The utility's operational Magnox reactors were considered "almost 100 per cent more expensive than LWRs." The AGR stations were all plagued by technical problems that translated into economic disadvantages compared to PWRs and BWRs built abroad.[48] Yet, the government remained skeptical about the safety of light-water reactors. In the end, it picked an alternative reactor type: the British-designed steam-generating heavy-water reactor (SGHWR). Officials hoped that this unique model would prove safer than a light-water reactor and more economical than a gas-graphite reactor. A sense of national prestige also influenced the decision. An interesting argument was that an indigenous design would shield the UK nuclear industry from negative developments abroad. In contrast, a fleet of British light-water reactors of American design would make the country vulnerable to accidents in other countries. The government anticipated, in particular, that the US-built light-water reactors that were being exported to the Global South might fail catastrophically. "If one of

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these blows up," it speculated, "the government will have no alternative but to shut down the LWRs in this country."[49]

The concerns over reactor (un)safety spread to the non-Western world, too. The Japanese government's advisory committee for energy called for research to improve plant safety "so that plants can be built on relatively soft foundations, underground, on islands, and possibly close to populations centers."[50] Yet, political and public opposition to the atom grew rapidly in the mid-1970s. The fear of dramatic accidents merged with environmental concerns about cooling water discharges and potential radioactive emissions. There were major local campaigns against planned projects. No Japanese utility could proceed with nuclear construction without engaging in "time-consuming negotiations with residents near selected sites, particularly with fishermen." The Japan Atomic Energy Commission (JAEC) attempted to appease the public by holding public hearings. Meanwhile, the Science and Technology Agency (STA) requested that the finance ministry "sharply increase spending on nuclear safety," especially regarding emergency core cooling issues.[51]

The Japanese nuclear industry suggested turning the problem of thermal pollution from large reactors into an opportunity. They proposed using the heated coolant "to promote regional industries and public works, such as marine culture, horticulture, and district heating systems."[52] The STA and the JAIF also proposed making nuclear power plants more popular at the local level by offering tax benefits and infrastructure investments, "including construction of fishing and other ports, roads, parks, and water systems."[53] This strategy was largely successful. In Hamaoka, for example, 120 miles southwest of Tokyo, local fishermen initially protested vehemently against Chubu Electric's plans to build a large-scale nuclear plant next to their fishing village. But the utility was able to proceed with the project beginning in 1971 after agreeing to pay "$2.4 million compensation for possible loss of catches because of coolant discharge into the Pacific Ocean."[54] A similar agreement was reached in 1975 with fishermen working near Kansai Electric Power's (KEPCO's) nuclear power plants, which were all located in Fukui Prefecture. The agreement gave the fishermen and their representatives "the right to inspect a plant before Kansai resumes operation after any shutdown that involves undue radiation leakage or excessive thermal discharge." The utility was also obligated to offer monetary compensation if the fishermen suffered damage. Moreover, KEPCO was to

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"help in fishery promotion," and to consult with and "seek understanding" of the fishermen when planning new plants or considering changes to existing ones. On this basis, a number of coastal villages with declining populations accepted nuclear power plants as a means of revitalizing their regions.[55]

In the Soviet Union and communist Eastern Europe, reactor safety was not publicly debated, but experts were concerned about the safety of the Soviet RBMK-1000 and VVER-440 designs. The RBMK (Chernobyl-type) reactor was regarded as the most problematic, because it easily became unstable. It also lacked a protective containment.[56] VVER plants were considered somewhat safer. These reactors were designed to prevent radioactive leaks during normal operation and to withstand minor accidents. But the breakdown of a main cooling pipe in the primary loop—internationally recognized as the "maximum credible accident"—was beyond what a VVER-440 plant could manage. The Soviets expected that, in that scenario, large amounts of radioactivity would escape into the environment. The implication was that VVER-440 plants must not be built in the immediate vicinity of densely populated areas.[57]

The risky features of the VVER-440 troubled the Finnish government and its state-owned utility Imatran Voima, which were pressured by the Kremlin to purchase a Soviet nuclear power plant in the late 1960s. The Soviet goal was to use Finland as a gateway to the Western reactor market. Worried about the VVER's inferior safety features, the Finns adopted a tough negotiation strategy with the Soviet reactor supplier. The Finnish delegation requested that the reactor be covered by a gas-tight steel containment structure. They also demanded that all key components be designed according to the American Society for Mechanical Engineers (ASME) standard. The Soviets found these demands unacceptable. Nevertheless, a deal was eventually worked out that, in effect, reduced the role of the Soviet Union to that of a subcontractor: Moscow would deliver the reactor pressure vessel and a few additional key components, but Imatran Voima would "redesign the power plant, adapt it to match Finnish requirements, manage the project as a whole and find subcontractors—in Finland and abroad—for those parts that Technopromexport did not provide." When the first reactor at the Loviisa NPP went critical in January 1977, the Soviet engineers who, along with Premier Alexei Kosygin, participated in the opening ceremony, were surprised to see their VVER-440 reactors covered by a massive steel containment of a

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Figure 4.1
The Loviisa nuclear power plant in Finland. *Source*: Photo by the author, 2003.

distinctly Western kind. The Finns congratulated themselves on the success of "Project Eastinghouse" (figure 4.1).[58]

The Finnish approach alerted Central and Eastern European countries planning similar projects. In 1972, at a nuclear engineering fair held in Basel, Switzerland, East German government officials approached their Finnish counterparts to inquire whether Wärtsilä, the Finnish industrial company responsible for building Loviisa's containment, might be willing to sell such containments to East Germany for its future VVER-440 plants. Czechoslovakia and Hungary were also reportedly interested in the Finnish containment technology.[59]

In the end, the idea of Finnish containment exports did not come to fruition. However, the strong Finnish and Central European interest in the technology convinced the Soviet Union that, to be attractive in the international marketplace, the VVER reactor needed to be updated from a safety point of view. The Hungarians, in particular, whose Paks NPP was in the planning stage in the early 1970s, pushed for a more modern reactor in

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their negotiations with Moscow. This ultimately led to a significantly modified version of the VVER-440 reactor: the VVER-440/213. It was recognized by both Western and Eastern experts as a clear improvement.[60] The only problem was that numerous RBMK-1000 and early VVER-440 reactors were already in operation or under construction in the Soviet Union and other communist countries, and none of these machines had the new safety components. This would have unfathomable consequences for the future of nuclear energy, both in the communist countries and worldwide.

The Troubled Everyday Lives of Nuclear Power Plants

Inevitably, the theoretical debate about potential problems in nuclear power plants was affected by real-world operational experiences. These experiences increased rapidly as more stations came online around 1970, and they were not particularly encouraging. The realities of the day-to-day operation of nuclear power plants worried utilities and regulators worldwide. From January 1972 to June 1973, for example, approximately 850 safety-related problems were reported at the thirty operational nuclear power plants in the United States. An internal AEC report noted, "The large number of reactor incidents—coupled with the fact that many of them had real safety significance, were generic in nature, and were not identified during the normal design, fabrication, erection and pre-operational phases—raises a serious question regarding the current review and inspection practices both on the part of the nuclear industry and the AEC."[61]

In 1974, US nuclear power operators reported a total of 1,421 "abnormal occurrences" in their plants. That same year, all boiling water reactors in the United States had to be temporarily shut down after pipe cracks were discovered at the Dresden NPP.[62] The nation's pressurized water reactors, for their part, were plagued by troubles with their steam generator tubes, which often corroded and leaked, leading to shutdowns. In 1973, US nuclear power plants reported a total of four hundred unplanned outages. More serious mishaps were around the corner, most notably a dramatic fire at the Browns Ferry NPP in 1975 that knocked out the plant's emergency core cooling system. Such events underscored the fact that many things could indeed go wrong in a nuclear power plant. In 1975, the Advisory Committee on Reactor Safeguards (ACRS) presented a list of twenty-seven unresolved generic safety problems with light-water reactors.[63]

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The harsh internal and public debates over unsatisfactory safety solutions, coupled with the track record of operational nuclear power plants, forced the AEC to adjust its position and take safety issues more seriously. James Jasper writes that the commission set out to develop "more elaborate, stringent, and complex standards for the design, construction, and materials of nuclear plants. The number of 'regulatory guides' grew from twenty-one in 1971 to 143 in 1978."[64] As a result, "the amount of material and labor required in reactor construction more than doubled over the decade of the 1970s." All of this led to rapidly increasing costs of nuclear power.[65] One study found that the capital cost of nuclear construction in the United States increased by 17 percent per year from 1972 to 1977. Another study estimated that, when considering both capital and labor, the costs increased sevenfold from 1969 to 1978, from $226/kW to $1,648/kW.[66] Direct costs aside, the required design changes resulted in construction delays. Additionally, the uncertainties about nuclear safety—reflected in divided expert opinion and a growing antinuclear movement—made investors skeptical. And Washington, under both Gerald Ford and Jimmy Carter, saw no reason to "rescue" the nuclear industry with federal funding.[67]

The final nail in the coffin was the partial meltdown of the Three Mile Island NPP's second reactor on March 28, 1979. In one of those great historical ironies, just twelve days before the accident, the Hollywood movie *The China Syndrome* premiered. The film depicted a nuclear incident—a near-disaster—that was remarkably similar to the real-life event in Pennsylvania. A full-blown disaster was eventually averted at Three Mile Island, but the accident gripped the nation in an unprecedented way as operators, manufacturers, and regulators struggled to understand what was happening in the reactor (figure 4.2).[68] According to sociologist Charles Perrow, the event was a "normal accident," one that could be expected to happen, rooted as it was in the plant's technological complexity and the "tightly-coupled" nature of its subsystems and components.[69] Nobody died at Three Mile Island. Yet the accident prompted both critics and regulators to call for additional safety features, which led to a further increase in plant complexity—not only at Three Mile Island but at all light water reactors, in the United States and globally. As a result, the cost of nuclear construction continued to grow, making the atom less attractive not only from a risk perspective but also from an economic point of view.

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Figure 4.2
The Three Mile Island unit 2 control room during the crisis in 1979. *Source*: US Nuclear Regulatory Commission (NRC).

Canada's nuclear program, which was based on heavy-water technology, developed along a somewhat smoother trajectory than its neighbor's. Yet, the CANDU reactors that were taken into operation were not without problems. Hydro Québec's Gentilly-1, the most troubled, became "a technological nightmare." It operated intermittently for a meager 184 days before it was permanently shut down in 1977 due to "mechanical and technical problems." Meanwhile, in Ontario, Douglas Point faced repeated outages due to "faulty pumps and valves deep within its system," and there were at least two radioactive spills into Lake Huron in 1970. Pickering and Bruce suffered cracks in the reactors' pressure tubes, which led to heavy-water leaks and costly backfits. There were also problems with the steam generators at several plants, necessitating a "big repair job." In the meantime capital costs of Canadian nuclear plants rose rapidly. The Point Lepreau reactor, for example, was projected at $466 million in 1974, but it ended up costing nearly $1.4 billion. In Ontario, inflation plus "more demanding regulatory design requirements" were seen to "triple the cost per kilowatt installed" during the 1970s. Among other things, the emergency core cooling systems at several plants needed to be modified.[70]

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Meanwhile, across the Atlantic, Britain's nuclear engineers found it hard to master the AGR version of the nuclear steam engine. Numerous design flaws necessitated costly modifications. The reactors were "built late, hugely over budget and never performed at the level they were designed for." The pioneering Dungeness B AGR station, which began to be erected in 1966, would later be remembered as "the single most disastrous engineering project undertaken in Britain," being "beset by delays, strikes and cost overruns."[71]

CEGB officials argued in the early 1970s that the older Magnox reactors provided "a safe, reliable and economic means of producing electricity."[72] In reality, both load factors and thermal efficiencies for the Magnox stations showed a downward trend, while the cost of producing nuclear electricity increased. By 1973, the average load factor for the nine Magnox plants was only 58 percent.[73] Meanwhile, the CEGB made an upward revision to the construction costs, taking into account the huge public investment in research and development that underpinned the Magnox reactor program. Critics also argued that the operating costs of the Magnoxes were artificially lowered by the practice of assigning a high value to the plutonium in the spent fuel. By the late 1970s critics alleged that the nuclear power business in the United Kingdom had "totally failed to deliver the cheap, plentiful and safe power that was promised" and that "it is clearly time that a halt was called to the whole disastrous program." This was despite the fact that UK nuclear power plants were generally considered safe and there were "few opportunities to challenge trust in UK regulators."[74]

In continental Western Europe, many of the large reactors that came online in the 1970s disappointed their owners. In April 1972, for example, an accident occurred during the start-up phase of the Würgassen NPP, one of West Germany's first large-scale plants. "A release valve opened inadvertently and could not be closed again. As a result, steam escaped from the reactor vessel into the condensation chamber." The reactor had to be shut down for six months. Then, in 1973, a leak in the primary steam pipe necessitated another, four-month closure of the same plant. From February 1974 Würgassen was down again for almost a year, because several key systems were found to be faulty and had to be replaced.[75] Another German plant, the Obrigheim NPP, was plagued by repeated steam generator tube leaks caused by intercrystalline cracks that no one knew how to explain.[76]

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In Bavaria, meanwhile, the Gundremmingen NPP was the scene of an accident that killed two mechanics in November 1975. Their deaths were caused by radioactive water that flashed to steam in a valve casing. Then, in January 1977, hot radioactive water flooded the plant's containment to a depth of two meters when the reactor feedwater valves failed to close. Unexpected cracks were subsequently found in the reactor's twenty-four-inch recirculation pipes. This necessitated backfitting with new types of steel. Five other German BWRs of similar design were forced to undergo the same modification.[77] The Biblis NPP on the Rhine also experienced malfunctions. In 1976, for example, twenty screws were found on bottom of the reactor vessel and hairline cracks were spotted in the feedwater tank.[78] The Brunsbüttel NPP on the Lower Elbe was another troubled plant. In 1978, a pipe leak caused two tons of radioactive steam to escape when plant operators overrode the automatic shutoff devices.[79]

In Sweden, the most problematic reactor was the second unit at Ringhals, a Westinghouse PWR. In September 1974, multiple charging pump failures had the Swedish nuclear industry in "something of an uproar" because the pumps were part of the plant's emergency core cooling system. Vattenfall, the responsible utility, complained loudly about the quality of the pumps, which had been manufactured by a Belgian company. The Belgians, it turned out, had substantial experience in making pumps for the fossil fuel industry but not for the nuclear industry. There were also steam generator problems with stagnant flows in the Ringhals reactor. In May 1975 the Swedish Nuclear Power Inspectorate published a report on scrams (emergency shutdowns) and operating failures at the country's four operational reactors. The report concluded that there had been 136 scrams between July 1974 and April 1975, 68 of which occurred at Ringhals-2. Ringhals-1, meanwhile, suffered from a crack in a main steam pipe that forced the plant to shut down for several months in the summer and fall of 1975.[80]

Internal reactor safety aside, a particular European problem took the form of repeated terrorist attacks against nuclear plants. In May 1975, one of the reactors under construction at Fessenheim in France was damaged when "two charges of plastic explosive were detonated on the reactor site."[81] A few months later the 70 MW Monts d'Aree station in Brittany suffered a similar attack. The terrorists broke through a wire fence into the plant compound and damaged a water inlet and filter system, as well as a ventilation chamber

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with plastic explosives. The Breton Liberation Front, a local anarchist group, claimed responsibility for the attack.[82] Then, in November 1976, a bomb was found at Ringhals in Sweden. A message from the terrorists said, "This is a last warning. Next time we will level the station to the ground."[83] More seriously, in December 1977 Basque terrorists attacked the Lemóniz NPP on the Bay of Biscay, whose first reactor had just been completed and was expected to go critical within a month. This was followed by an even more violent action in March 1978, when "a Basque terrorist bomb blew the Lemóniz-1 reactor vessel lid off and blasted a hole 1½ meters wide in one of the unit's three steam generators." Tragically, the attack killed two plant workers and injured fourteen.[84] A year later a bomb exploded in a material-storage depository at the Leibstadt NPP in Switzerland, which was under construction on the High Rhine.[85]

As in the United States, accidents and concerns over poor reactor safety led to tougher regulatory requirements across Western Europe. Backfits became necessary and construction costs increased. In Germany, nuclear power plant capital construction costs increased from $130/kW in 1967 to $200/kW in 1971. Meanwhile the prices of some components rose by up to 100 percent, largely due to the "tightening of regulations."[86] But that was only the beginning. From 1972 on, Germany saw a further tightening of ECCS regulations, forcing utilities to replace existing ECCSs in operational plants with newer, more expensive ones. Burst-proof reactor designs added to these costs. Industry analysts estimated that pressure vessel burst protection would cost at least $30 million, perhaps as much as $100 million, for a 1,300 MW plant. BASF, which had hoped to pioneer the construction of a burst-proof reactor at Ludwigshafen, reported that the project's cost increased by 330 percent during the eight-year licensing period due to "more and more safety requirements." During the same period, the costs of a "standard" (non-burst-proof) nuclear power plant rose by 190 percent.[87]

In the end, European electricity consumers were left to shoulder the soaring costs. For example, the Spanish government decided in November 1975 to raise electricity rates by 8 percent for residential consumption and by 20 percent for industrial, transportation, and public lighting consumption "to help finance nuclear plant construction." Similarly, in early 1976, Électricité de France (EDF) increased its rates by 15 percent to finance its substantial nuclear investments and cope with rising oil prices.[88] The Dutch contribution to West Germany's Kalkar fast breeder project was financed

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through a monthly surcharge on each household's electricity bill. This "Kalkar levy" sparked public outrage in the Netherlands, and the funding mechanism became a primary target of the Dutch antinuclear movement.[89]

Overall, however, the economic viability of nuclear power was debated less in Europe than in the United States, chiefly because few European utilities were exposed to market forces. While European governments and utilities, many of which were state-owned, followed the US debate over "nuclear versus coal" with interest, they tended to be more concerned with issues such as energy dependence and resource scarcity than with economic factors. Most West European countries lacked sufficient fossil fuel reserves and saw nuclear power as a means of reducing coal, oil, and gas imports, even though it was far from clear that nuclear power would be cost-effective. Thus, decisions to invest or not in the atom became a matter of national strategy rather than corporate calculation.

The Soviet Union and the communist countries in Central Europe were, in theory, shielded from capitalist profitability expectations. In reality there were strong pressures to develop nuclear energy as quickly as possible to save money and time. This led to difficult trade-offs between economic efficiency and nuclear safety. Moreover, the Communist Party was reluctant to acknowledge and learn from the numerous failures that were part and parcel of the everyday lives of Soviet nuclear power plants. The result was a growing number of accidents and incidents. Boris Shcherbina, who headed the special commission to manage the Chernobyl accident, found that in the five years preceding that disaster, "there were 1,042 accidents at our nuclear power plants, yet, since 1983, the Ministry of Energy and Electrification has not had one meeting to discuss reactor safety."[90] Some of the most serious accidents occurred at the Leningrad NPP in 1974–1975, Beloyarsk in 1977–1978, the first Chernobyl unit in 1982, and Balakovo in 1985. In Central Europe, the Greifswald NPP in East Germany suffered a near-disaster in 1975, while the pilot-scale A-1 heavy-water reactor in Bohunice, Czechoslovakia, had to be closed permanently after two serious accidents in 1976 and 1977.[91]

More than anything else, Soviet nuclear engineers feared accidents resulting from power outages, which were frequent in the communist world. Nuclear power plants needed access to external electricity grids to power their cooling water pumps, and many doubted that the Soviet grid could handle this task in a reliable way. Since the RBMK-1000 and VVER-440

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reactors lacked containment, ensuring that the pumps would never grind to a halt was even more important in the East than in the West. It became imperative to ensure the availability of backup power sources in order to cope with a station blackout. The main backup power source took the form of diesel generators. But the Soviet-made diesel generators were of poor quality and slow to start. Safety experts suspected that these fossil-fueled emergency systems might not come to the rescue quickly enough in the event of an accident.

In April 1986, an experiment was carried out at the Chernobyl NPP in Ukraine to solve this problem. Unfortunately, it did not work out as planned. Instead, the experiment triggered the world's worst nuclear disaster to date (figure 4.3). The test rendered the station's fourth reactor highly unstable, and the operators were unable to shut it down. Much to their surprise, when they pressed the SCRAM button, the fission process did not stop but rather intensified. As one Soviet nuclear engineer described the event, "The reactor's power at first decreased just a little, and suddenly and with growing speed sharply increased until the reactor underwent a surge that ended in a massive explosion."[92] A large portion of the core "vaporized into the air." Radioactive gases poured from the disaster site for several weeks. Millions of curies of radioactivity were released, "comparable to several large nuclear warheads."[93]

Japan's most problematic nuclear station was the Mihama NPP, located on the Sea of Japan (figure 4.4). In June 1972, the station's first reactor had to be shut down due to leaks in both steam generators. Radioactivity levels in the secondary circuit increased up to a thousand-fold. Two thousand of the eight thousand tubes that made up the reactor's steam generators had to be plugged, and the reactor was taken out of operation for over a year. Soon after it was restarted, new leaks were detected and the reactor came to a standstill again for over two years. There were similar leaks in the Mihama-2 unit.[94] The first reactor at Fukushima Daiichi also experienced problems, in the form of cracks in piping that were discovered during a scheduled outage in the fall of 1974. The plant's second reactor had to be shut down for four months in 1975 due to "a fuel channel box vibration problem." And at Tsuruga, the core spray piping had to be replaced, leading to an unplanned eight-month shutdown. The total capacity utilization of Japan's nuclear units dropped to a dismal 36 percent in 1975.[95]

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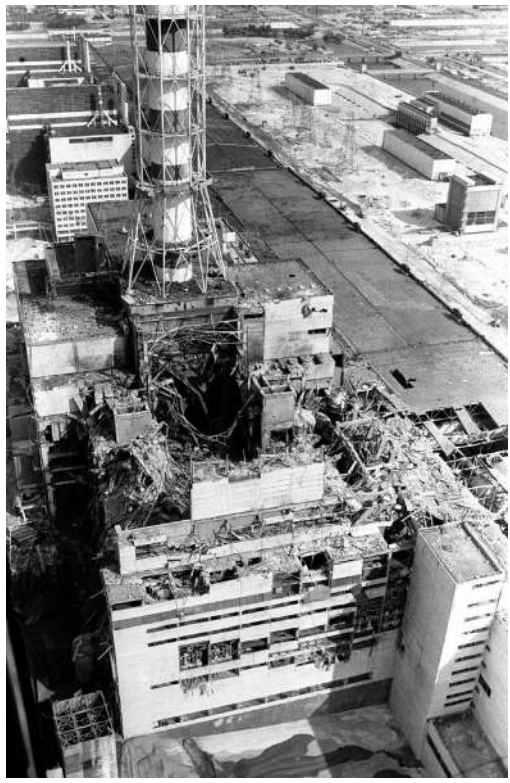

Figure 4.3
Chernobyl's fourth reactor bloc after the 1986 disaster. *Source*: IAEA.

The year 1976 was not much better. There were problems in four of the country's nuclear power plants during their shutdown periods. For example, one of the fuel assemblies at the Takahama NPP was found to have been damaged. Meanwhile, tiny cracks were discovered in the feedwater and control-rod water nozzles at Fukushima Daiichi's first reactor. In addition, a number of fuel bundles leaked fission products. The average capacity factor of Japan's growing nuclear fleet remained disappointingly low. By 1978 it had climbed to 57 percent, which was better than a few years earlier but far below the engineers' expectations.[96]

In response to this development, the Ministry of International Trade and Industry (MITI) launched an "improvement and standardization program." It aimed to address what was interpreted as deficiencies in the transfer of

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Figure 4.4
The Mihama NPP, seen from the nearby Nyu fishing village. *Source*: Photo by the author, April 2024.

US reactor technology to Japan. MITI hoped "to achieve higher equipment reliability and operational efficiency and to lower workers' radiation exposure." Meanwhile, regulatory requirements were stiffened, partly due to the growing number of incidents and partly in response to new theoretical insights about what could go wrong in emergency core cooling and other safety-related systems. The 1978 Miyagi earthquake, meanwhile, led to a revision of the Japanese Buildings Standards Act. These developments stimulated safety improvements at the nation's nuclear power plants, leading to increased operational availability. But they also made nuclear construction more expensive. On average, the Japanese plants that were completed in the late 1980s and 1990s cost nearly three times as much as those that began operating in the 1970s.[97]

Concerns about the safety of Japanese nuclear power plants did not subside, particularly regarding older plants not covered by the improvement and standardization program, such as the Tsuruga NPP and the first four reactors at Fukushima Daiichi. The stations' envirotechnical entanglements also remained a major concern. In March 1981, water from the filter sludge storage tank at Tsuruga flowed onto the storage building floor and then

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into the power plant's wastewater canal "because a valve was inadvertently not closed." The incident caused public dismay in Japan, especially since the sale of fish caught in Tsuruga Bay had to be suspended. Such mishaps did not bode well for the future.[98]

Fuel Cycle Worries

In addition to concerns about reactor safety and worries about the atom's envirotechnical entanglements, several dilemmas linked to the nuclear fuel cycle began to attract worldwide attention in the mid-1970s. In the early days of atomic energy, governments and utilities had assumed that they would be able to close the nuclear fuel cycle and effectively manage their nuclear waste—if not immediately, then in due time. As more and more nuclear power plants came online, however, the need for solutions acquired a new urgency, especially at the "back-end" of the fuel cycle. As discussed in chapter 3, many attempts to reprocess spent nuclear fuel suffered serious setbacks, and there was a lot of controversy surrounding spent fuel transports. In the meantime, large amounts of spent reactor fuel began piling up at reactor sites. In the United States especially, more and more utilities found that they were running out of storage space. At the Atomic Industrial Forum's fuel cycle conference, held in March 1974, there were intense discussions on possible ways "to alleviate the growing threat of a spent-fuel backlog." Some analysts feared that such a backlog "could eventually force the shutdown" of US civilian reactors. In this situation, efforts gradually shifted from getting reprocessing plants up and running to expanding interim storage capacity. The spent fuel crisis horrified the nation's utilities and discouraged many of them from investing further in nuclear energy.

Another concern was the unresolved problem of radioactive waste disposal, which, for the time being, was considered a separate challenge from managing spent fuel. The failure to establish a geological repository for high-level waste at Lyons, Kansas, made US utilities and reactor vendors nervous. Intervenors and activist groups began arguing that no more nuclear power plants should be licensed unless they could demonstrate that the waste could be "safely disposed of." The NRC protested, arguing that "the technology for disposal is reasonably available." The US Supreme Court supported this position. Individual states, however, continued to insist that the utilities must present a concrete solution to the waste problem. Thus,

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in June 1976, California passed a law prohibiting new nuclear plants from being built "until a satisfactory method for dealing with the waste problem was demonstrated."[99] Soon after, in October 1976, a ruling by the US Court of Appeals suspended construction permits for New Hampshire's Seabrook NPP "indefinitely," citing inadequate consideration of waste management in the project's environmental review. Overall, there was growing pressure on the US nuclear industry to demonstrate progress in waste management. Yet the technology of waste disposal remained uncertain, and all proposed solutions were fraught with technical problems.[100]

The Canadians also struggled to find a solution to the waste challenge. In addition, there were troubles at the "front-end" of the nuclear fuel cycle in the form of health and safety concerns in uranium mining areas such as Elliot Lake. Strikes occurred among workers in this area in 1974.[101] When Ontario's regional government set up a special commission—the Porter Commission—to explore the dilemmas of nuclear power in the context of electric power planning, uranium mining and nuclear waste management were identified as more serious issues than reactor safety. The greatest challenge was seen as managing thousands of tons of spent nuclear fuel, "which at all times must be isolated from the earth's ecosystem."[102]

Meanwhile Britain experienced recurring troubles at its Windscale (Sellafield) reprocessing and waste treatment facilities. As we have seen, there were numerous accidents and radioactive leaks at this site on the Irish Sea. From 1975 on, public criticism grew further in connection with the debate about the UK becoming "the world's nuclear dustbin." The back-end of the nuclear fuel cycle was increasingly viewed as a serious threat to the future of nuclear power in Britain. The Royal Commission on Environmental Pollution, chaired by the physicist Sir Brian Flowers, pressed for a solution. Following the international trend, Flowers recommended that "there should be no substantial expansion of nuclear power until the feasibility of a method of safe disposal of high level wastes for the indefinite future has been established beyond reasonable doubt." As in Canada, surveys showed that UK residents viewed radioactive waste as a greater risk to themselves than a major nuclear accident.[103]

West Germany was another country where controversies over spent nuclear fuel and radioactive waste intensified in the mid-1970s. The federal government under Chancellor Helmut Schmidt supported the creation of a centralized fuel cycle complex, comprising spent fuel storage basins,

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a reprocessing plant, plutonium processing facilities, and a large underground waste repository. But the project progressed only slowly and costs escalated in the meantime. By early 1976, the German chemical industry signaled that it wished to exit the plutonium economy because it no longer seemed to be a profitable business. This led to difficult financial discussions during which the federal government made it clear that it would not pay for the fuel cycle facilities. Instead, following the "polluter-pays" principle, the utilities would have to bear most of the costs. To put pressure on them, the Interior Ministry announced that it would "not license any new nuclear power plants until the reprocessing/waste problem is settled," thus following the example of California and Britain.[104]

By mid-1977, it was widely recognized that failing to advance reprocessing and waste management effectively meant a moratorium on constructing new reactors in the Federal Republic.[105] It was hoped that selecting Gorleben, in Lower Saxony, as the site for the German fuel cycle complex would end the stalemate. However, the opposite occurred. Following the Three Mile Island accident and the growing antinuclear movement in Germany, it became politically impossible to continue with this ambitious project. It would take another decade before the utilities finally abandoned their reprocessing ambitions. In the meantime, they focused on ensuring the availability of interim storage facilities for spent nuclear fuel.[106]

The Swedish nuclear industry proved surprisingly successful at navigating the political twists and turns around spent fuel and waste. After the September 1976 parliamentary elections, the new government led by Center Party leader Thorbjörn Fälldin—who was explicitly antinuclear—presented a "Californian" bill specifying that all "issues relating to the management of spent fuel and high-level waste must be resolved before a reactor can be put into operation."[107] The country's nuclear operators responded flexibly by signing reprocessing contracts with BNFL and COGEMA. The utilities also announced a $7 million research program on safe methods of nuclear waste storage. The Swedish Nuclear Inspectorate, controversially, accepted these measures as satisfactory and allowed two new reactors to start up. Yet the waste issue remained fraught with tension. It would remain one of the main bones of contention in Swedish nuclear policy for decades to come.[108]

The waste challenge was considered equally important elsewhere in western Europe. In Denmark, for example, which hoped to build at least two

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commercial reactors, the utilities had originally assumed that they would be able to "export" their spent fuel for reprocessing without waste return. The new waste policies adopted by Britain and France in the mid-1970s changed the outlook. Since the high-level waste resulting from reprocessing would now be returned to the country of origin, it would have to be stored in Denmark. The government pressed the utilities to come up with a storage solution. In August 1976, the ruling Social Democratic Party, supported by a majority of parliament members, announced that it would defer the introduction of nuclear power in Denmark "until an acceptable solution to the nuclear waste problem has been found."[109]

Austria's plan was to reprocess its spent fuel in France, but, as in the Danish case, it was unclear what would happen with the resulting high-level waste. In July 1977, the country's ruling Social Democratic Party passed a resolution stating that the Zwentendorf NPP, which was more or less complete at the time, "should be given a permit for test runs only after a solution to its waste problem has been found." Facing lack of progress, the issue ultimately grew so contentious that the Austrian parliament decided to hold a national referendum to let the public decide whether the plant should be allowed to start up. Pronuclear Chancellor Bruno Kreisky, desperate to save the completed station, declared he would resign if Austrians voted against commissioning the plant, but to no avail. The vote, held in November 1978, four months before the Three Mile Island accident, resulted in an unexpected victory for the antinuclear side. Thus, the Zwentendorf NPP was not allowed to start up. A few weeks after the referendum, the Austrian parliament adopted an antinuclear law stipulating that "installations intended to generate electrical energy by nuclear fission for the purpose of energy supply may not be erected in Austria."[110]

The Global South's fuel cycle worries were of a different kind. At the outset, many countries assumed that they would be able to develop domestic nuclear fuel cycles. The underlying idea was that this would pave the way for independence from foreign uranium supplies and foreign conversion, enrichment, and reprocessing services. Countries such as India, Pakistan, Iran, Brazil, and Argentina aimed to create their own plutonium economies, with plans to use large quantities of this fissile material in domestic breeder reactors and, in some cases, nuclear weapons. Argentina, which hoped to "achieve total control of the natural uranium fuel cycle," even aimed to become a major exporter of plutonium produced through

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domestic reprocessing of spent fuel from its heavy-water reactors.[111] But this presupposed that uranium and plutonium were treated as ordinary materials that could be easily recycled and circulated internationally. In reality, the intended fusion of the traditional circular economy ideal with the Janus face of nuclear science proved to be utterly problematic. Western governments grew increasingly wary of the Global South's nuclear ambitions, viewing with horror the prospect of large volumes of plutonium circulating among nations with unclear military intentions and unstable political regimes. Over time, this would prove to be one of the most serious obstacles to nuclear expansion in the Global South.

Conclusion

Until the early 1970s, nuclear power was promoted as the one and only way to counter fossil fuel scarcity and solve the environmental problems resulting from the excessive burning of coal and oil. In fact, the nuclear industry invested considerable sums in research to demonstrate the imminent depletion of fossil fuels and their significant impact on health and the environment. The AEC even recruited the famous peak-oil theorist Marion K. Hubbert for this purpose. Nuclear proponents also showed early interest in the phenomenon of global warming—a topic that we will revisit in chapter 6.[112] Many governments took the scientific reports published on these subjects seriously, concluding that large-scale investments in nuclear power were necessary because there were "no alternatives." This paved the way for the extravagant nuclear programs that were launched across the world in the years around 1970.

The grand atomic visions, however, soon clashed with the technological, economic, and political realities of nuclear power. In principle, the general public was prepared to accept nuclear power in return for guarantees that no serious accident would occur. However, precisely this challenge—guaranteeing nuclear safety—turned out to be anything but straightforward. Besides scientific and theoretical debates over the safety of the nuclear steam engine, the actual everyday operation of nuclear power plants worldwide was disconcerting. Already before the Three Mile Island accident and the Chernobyl disaster, numerous incidents and accidents damaged the nuclear social contract. In addition, the efforts to improve the safety record with the help of additional layers of technology created a cost-complexity

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trap, making nuclear power increasingly expensive and raising doubts about its economic viability. Concerns about the envirotechnical aspects of nuclear power plants, which had sparked the first protests against the atom, also lingered, as did many questions about the nuclear fuel cycle.

The nuclear industry and its proponents were not helped by the perceived connection between nuclear power and nuclear weapons. They were also hurt by the fear that nuclear power might require or stimulate the rise of a more authoritarian state—a "nuclear state" (*Atomstaat*), as the Austrian antinuclear activist Robert Jungk famously called it in a 1977 publication.[113] The nuclear industry felt misunderstood and criticized unfairly. It sought to assure the world's political leaders and the general public that, though not free from problems, nuclear power could be made safe, reliable, and economical. Yet the future of nuclear power began to appear less appealing to many stakeholders. Especially when it turned out that fossil fuels, after all, were not that scarce and that alternatives to nuclear power might become available, it became difficult to sustain the erstwhile visions. In the next phase, one country after another took a step back from their nuclear plans and commitments, leading to the cancellation of planned and ongoing projects, refusals to take completed plants into operation, and eventually, the closure of operational reactors.

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5 The Global Stagnation

Atomic disenchantment was in the air almost everywhere in the world as the 1970s drew to a close. The original fascination with nuclear fission that had characterized the first postwar decades seemed to belong to a distant past. The antinuclear movement had gained unprecedented strength. Governments were growing increasingly skeptical about the atom, as were many utilities. Some remained optimistic about the future, envisioning that the problems the industry faced could be overcome. In more and more countries, however, actors began looking for alternative ways to meet their energy needs. What followed was a complex interplay between politics, economics, and technology in different national settings, whereby the atom's three troubled marriages meshed with each other in a fierce struggle for and against an atomic future.

The Tide Turns in North America and Britain

In the United States, the combination of stringent environmental standards, the need for additional safety measures, and fuel cycle dilemmas created a snowball effect of problems and costs for the nuclear industry. In many cases utilities concluded that it was simply not worthwhile, from an economic point of view, to continue with planned and ongoing plant construction. The number of cancellations increased, and by late 1975 it already seemed clear to many analysts that nuclear power expansion in the United States was coming to an end.[1] In total, orders for over one hundred large reactors were canceled, and no new orders were in sight. In 1974, US utilities began construction on thirteen new reactors that would actually become operational, which was still a fairly high number. In 1975, the

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number dropped to nine, and in 1976 to seven reactors. By 1977, construction activity had collapsed altogether, with only three new construction starts, followed by a single one in 1978. No further nuclear reactor projects were initiated in the United States after that.[2] On the eve of Three Mile Island, the American atomic age had come to a full stop. Analysts described nuclear power as having a "corpse-like appearance." The industry was seen as "slowly, very slowly, bleeding to death." Antinuclear groups declared, "We have won the war."[3]

The situation in Canada was not much better. By 1975, the Canadian nuclear program was facing the same "sort of questioning that has long been applied to US nuclear power." Dozens of environmental and antinuclear groups formed the Canadian Coalition for Nuclear Responsibility (CCNR) and set out to gather hundreds of thousands of signatures "to force a national debate on energy policy and the role of nuclear power."[4] Initially, the focus was on mesolevel "unknowns" such as, in the case of Nova Scotia, "what might happen as a result of discharging 10 million gallons of 20-degree warmer water every minute into the smallest and richest lobster fishing district in the province." Concerns over reactor safety and radioactive waste further fueled criticism. There was also the specter of nuclear-weapons proliferation, which was accentuated by AECL's ambitions to become a leading exporter of nuclear technology to the Global South. Following India's nuclear explosion in 1974, a feat made possible by Canadian exports of nuclear technology, difficult negotiations ensued over reactor exports to Argentina and South Korea. Antinuclear groups such as the Voice of Women demanded that Ottawa stop selling CANDU reactors to "shaky dictatorships." The Indian test, they argued, showed that there was no such thing as a "peaceful atom."[5]

The Porter Commission, mentioned in the preceding chapter, recommended continued investments in nuclear energy, and CCNR's quest for an all-Canadian moratorium on nuclear development fell on deaf ears.[6] Nevertheless, numerous proposed projects failed to move forward. For example, Manitoba Hydro, which had already picked a site at Lac du Bonnet for its first nuclear station, announced in 1978 that it gave up its nuclear visions "for the indefinite future on the heels of revised estimates showing slowed growth of electricity demand."[7] In Nova Scotia, Premier John Buchanan's decision in 1980 to pull out of a united regional Maritime Energy Corporation was seen as marking "the end of Nova Scotia's flirtation with nuclear

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power and the ultimate victory of public pressure over nuclear developmentalism."[8] Envisioned nuclear projects in other provinces were likewise canceled or postponed indefinitely. After the start of construction on Ontario's Darlington NPP in the early 1980s, no further nuclear power plants were built in Canada. The atom's share of the nation's electricity mix eventually peaked at 19 percent in 1994 and then began to decline.[9]

Britain's grand nuclear plans also failed to materialize. This was so despite the fact that the nuclear industry continued to enjoy government support. In December 1979, Margaret Thatcher's new government announced a new long-term nuclear power program, insisting that Britain must build multiple new reactors and increase the share of nuclear energy in the British electricity mix. Judging optimistically that "the lessons of events at the Three Mile Island station in the United States have been learnt," the Conservative government recommended investing in US-style light-water reactors. In this way it hoped to bypass the crisis plaguing the country's safe but expensive gas-cooled reactors and the failed SGHWR program.[10]

As before, however, not every Briton was convinced that the light-water reactor was safe enough. A lengthy inquiry into the nation's first PWR project, the Sizewell B NPP, followed. From 1983 to 1985, it produced nearly three thousand files of statements and evidence.[11] The reactor was eventually given the green light, but no further PWR projects were initiated. Thatcher's ambition to phase out state ownership of utilities contributed to this outcome; the privatization of the electricity industry quickly exposed the true costs of building and operating nuclear power plants as well as managing spent nuclear fuel and radioactive waste.[12] In the neoliberal marketplace, investors found it wiser to invest in nonnuclear energy sources. Coal remained the main source of electricity in Britain until the end of the millennium. Then, natural gas from the North Sea, burned in highly efficient combined-cycle turbines, took over. No new nuclear capacity was added. In parallel, the old Magnox reactors began to be taken out of operation, starting with the Berkeley station on the Severn estuary, which went offline in 1988. In the 1990s, then, the nation's fast breeder program was terminated.[13]

Diverging Paths in Continental Western Europe

In Western Europe, a divide emerged between countries that had commissioned or begun constructing at least one large reactor, and those that

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had not yet done so, when the issues of reactor safety, spent fuel management, and radioactive waste disposal entered the public realm. The first group included France, Germany, Belgium, the Netherlands, Sweden, Finland, Switzerland, Austria, Italy, and Spain. The second group comprised Denmark, Norway, Ireland, Portugal, Greece, and Luxembourg. As of the early 1970s, both groups thought it self-evident that nuclear power would become a central component of their future energy supply; what differed was the degree of perceived urgency of nuclear investment and the extent to which governments and domestic industries aimed to play an active role in nuclear innovation. Many of Europe's smaller nations did not aspire to become technological leaders. They merely sought a way to meet their rapidly growing electricity demand. Under such conditions, some of them deemed it more appropriate to wait for developments in the larger countries than to rush into uncertain nuclear investments.

But then the scene shifted. The European antinuclear movement, which saw its breakthrough in 1974, made governments and utilities in many small countries increasingly hesitant. So did the far-from-convincing track record of operational nuclear power plants in the larger countries, reports about escalating construction costs worldwide, persisting envirotechnical dilemmas, the spent fuel and waste challenge, and the slowdown in electricity demand growth. The result was that nuclear planning shifted from near-commitment to reactor projects to a prolonged wait-and-see approach. Ultimately, none of the countries in the second group would build any nuclear power plants. The share of nuclear energy in their electricity mixes thus remained at zero—a surprising outcome given the visions and plans that had been formulated in the years around 1970.[14]

The West European nations that had already begun investing in nuclear power were in a different position. In these countries, the nuclear industry was able to build on the momentum of completed projects and ongoing construction. It managed to do so in spite of strong antinuclear movements. The opponents managed to prevent several finalized or nearly completed plants from becoming operational, including Austria's Zwentendorf NPP, Germany's Kalkar fast breeder, the twin reactors at Lemóniz in Spain, and Switzerland's Kaiseraugst NPP near Basel. In the history of antinuclear activism, these names would live on in heroic stories about victorious struggles against the atom. But the nuclear industry was also able to claim partial victory, as it managed to complete a number of

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controversial plants that were under construction and prevent closure of numerous operational ones.

Yet, by the turn of the millennium, three West European countries with significant investments in nuclear power had opted to abandon the atom. The first was Austria, whose nuclear program was terminated after the 1978 national referendum. Pronuclear advocates hoped for another public vote so that the Zwentendorf NPP might be revived. But this never happened, and the plant did not go into operation (figure 5.1). Austria's second nuclear power plant, which was planned to be built in Stein/St. Pantaleon, was also abandoned, even though an enrichment contract had already been signed with the Soviet Union.[15]

A decade later, Italy ditched nuclear power. This was a radical turn of events involving the premature closure of several operational plants. The road to the Italian phase-out can be traced back to 1977. That fall, following a surge in antinuclear activity, the national energy plan was reevaluated in a parliamentary debate. An earlier goal of bringing 12,000 MW of nuclear capacity online by 1985 was reduced to 8,000 MW and then to 6,000 MW. But the opponents wanted the government to back down completely from the atom. When the country's leading energy experts and government officials met in May 1978 to analyze the situation, they noted that a range of mesolevel problems prevented nuclear expansion. It seemed almost impossible to find sites that met all demands and that pleased all stakeholders. There were concerns over seismic activity, cooling water scarcity, thermal pollution, and in the Po Valley, flooding. Coastal sites remained problematic because they conflicted with the tourist industry. Given this impasse, ENEL, the state-owned electricity company, began to view investments in new fossil power plants as a more realistic option.[16]

The Italian government made another attempt to boost nuclear development in the early 1980s. In October 1981 it adopted a revised energy plan that included construction of three new nuclear power plants: one at Trino Vercellese in Piedmont and two at unspecified sites in Lombardy and Puglia. Each plant was to have two 1,000 MW PWRs. Moreover, in 1982 the government allowed construction of the contested Montalto di Castro NPP in southern Italy to commence. All projects remained highly controversial, however, and the future of nuclear power in Italy remained in limbo.[17]

In the wake of the Chernobyl disaster, the Italian Green Party, supported by the Socialists and Communists, initiated a national referendum on three

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Figure 5.1
Remnants of Austria's Zwentendorf NPP, which was completed but never taken into operation. The photo shows the reactor building and the cooling water outlet. *Source*: Photo by the author, May 2024.

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hotly debated issues related to the nuclear program. The most controversial was a law that allowed the central government to determine the locations of new nuclear power plants if the relevant region failed to do so within a specified timeframe. Voters overwhelmingly supported abolishing this law. The government concluded that the result made it impossible to build new nuclear power plants in Italy. Construction of the first reactor at Montalto di Castro, which was now nearing completion, stopped, as did preliminary work at the other prospective sites. More radically, the government decided to close the nation's operational reactors—the Latina, Enrico Fermi, and Caorso plants—along with several fuel cycle facilities. One Italian NPP was actually completed: the Cirene pilot-scale plant, an Italian version of the CANDU reactor type. This 40 MW plant continued to be constructed after the 1987 referendum and was completed in 1988. Yet it was never allowed to go into operation. The last kilowatt-hour of nuclear electricity in Italy was generated in July 1990.[18]

The third European country to abandon nuclear power was Germany. There, the antinuclear movement gained unprecedented strength beginning in 1975. Governments at the federal and state levels also grew more skeptical about nuclear power as the 1970s progressed. In December 1977, the Social Democrats, who ruled at the federal level together with the Free Democrats, presented a new energy program that backed down from their earlier nuclear enthusiasm. The party announced its support for increased reliance on coal combined with energy conservation measures. Nuclear power was to play a "limited" role only. The new program was confirmed in July 1979 and again in January 1980. Following the Chernobyl disaster a few years later, the Social Democrats decided to advocate for a complete phase-out of nuclear power.[19]

In parallel with this overarching debate, the fate of individual German nuclear power plants was fiercely fought over on the federal and state levels as well as in the courts. Some projects survived this political and legal drama, while others did not. In a few cases, utilities withdrew from planned reactors more or less voluntarily in the face of lower than expected electricity demand, rising costs, tightening safety and environmental regulations, and public and political opposition. BASF, for example, opted to cancel its much-publicized Ludwigshafen project in late 1976, citing high costs, while PreussenElektra backed out of its planned Borken NPP following the 1977 Wyhl verdict. In other cases, the utilities tried to move ahead with construction,

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though often in vain. In February 1977, for instance, the Mülheim-Kärlich NPP on the Rhine was stopped—albeit only temporarily—by a court ruling, based on a new assessment of seismic risk. The planned Hamm NPP, for which VEW, a utility, applied for a construction permit in July 1975, was caught in a protracted licensing process, and the project never took off. RWE, the Federal Republic's largest utility, failed to move forward with its reactor projects at Vahnum on the Lower Rhine and with two more 1300 MW units at Biblis. Other planned German nuclear power plants that failed to materialize included the reactor projects at Meissenheim on the Upper Rhine, Schwörstadt on the Swiss border, Gersthofen on the Lech River, Marienberg near Rosenheim on the Inn, Pleinting on the Danube, Rysum-Emden and Cuxhaven on the North Sea coast, and Altgarge and Langendorf on the Elbe.[20]

In 1982 the pronuclear Christian Democrats took over the federal government after the Free Democrats switched coalition partners. During their tenure, West German utilities managed to complete nine reactor projects that had begun construction in the 1970s, including the controversial Brokdorf NPP, plus three new reactors. The Kalkar fast breeder, by contrast, was not allowed to start up, despite being fully completed by mid-1985. The reactor survived a complex court litigation but was denied an operating license by the regional government of North Rhine-Westphalia.[21] Meanwhile, a number of operational reactors were shut down. These included three pilot-scale projects that had been operating since the 1960s, but also two newly constructed plants: the Mülheim-Kärlich NPP (which eventually received approval) and the pioneering THTR-300 high-temperature reactor at Hamm-Uentrop. Both operated for just over a year before closing due to safety concerns. The first reactors at Lingen and Gundremmingen, for their part, never recovered from the 1977 accidents and remained closed, awaiting decommissioning. In 1994, the troubled Würgassen NPP joined the club of closed German nuclear stations.[22]

Despite these cancellations and shutdowns, the share of nuclear power in the West German electricity mix climbed to around 30 percent in the 1990s thanks to political support from Chancellor Helmut Kohl's government. Yet the country remained deeply divided over its atomic future. Deep-seated concerns about reactor safety, environmental issues, and the spent fuel dilemma persisted among large parts of the population. Politically, both the Social Democrats and the newly formed Green Party, which

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emerged from the antinuclear movement and entered the Bundestag in 1983, continued to oppose nuclear power. When a new red-green government was formed in 1998, it took immediate steps to phase out nuclear energy. Two years later it reached an agreement with the country's utilities to successively close all German nuclear power plants.[23]

Antinuclear sentiments were no less prominent in Sweden, Belgium, Switzerland, and Spain in the 1970s and 1980s. Nevertheless, the momentum of past planning and construction enabled nuclear power to become a significant contributor to the electricity mix in all four countries. In the Swedish case, Olof Palme's Social Democratic government decided early on to abandon its support for twenty-four large reactors, citing "risks associated with nuclear reactor safety and spent fuel management." A 1975 energy bill stated that "we do not yet have full clarity on the economics of nuclear power. The rising capital costs and the disruptions that have occurred have raised concerns."[24] Yet construction continued on twelve large reactors. It did not help that Thorbjörn Fälldin, the Center Party's antinuclear leader, took over as Prime Minister in 1976. Nor did it help that the parliament, following a national referendum held in March 1980, decided to close all nuclear power plants by 2010. The antinuclear political parties only managed to enforce the shutdown of two of the country's twelve reactors. The remaining ten reactors remained in operation, because no one was in favor of switching to fossil fuels and there was widespread skepticism about the potential of renewables to fill the expected electricity generation gap from premature reactor closures.[25]

In Spain, the utilities concluded that they had overinvested in nuclear power. In the face of lower than expected electricity demand, there was simply no need for the twenty or so large reactors they had planned. The problem was that they had already embarked on construction of numerous "unnecessary" plants, and by the late 1970s they found themselves seriously in debt. It was therefore somewhat of a relief for the utilities when, in the autumn of 1983, Felipe González's newly elected Socialist government announced a moratorium on further nuclear construction. This allowed the utilities to claim compensation. Indeed, the moratorium was only partly a response to strong antinuclear sentiments in the country; the government portrayed it first and foremost as a much-needed "rationalization" of the utilities' business plans and "the only viable option to restore their wrecked finances." Five reactors under construction, four of which were nearly

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complete, were abandoned. But the nation's already operational reactors remained unaffected, and by 1989 they generated as much as 38 percent of Spain's electricity.[26]

Switzerland followed a similar path. In 1988, the Swiss antinuclear movement celebrated the final abandonment of the controversial Kaiseraugst reactor project. Four other planned plants—at Graben on the Aare, Verbois near Geneva, Rüthi in St. Gallen, and Inwil near Lucerne—were likewise given up. In a 1990 national referendum on the future of nuclear power, the antinuclear side emerged victorious: 54.6 percent of the electorate supported a ten-year moratorium on building new plants. But the nation's five existing reactors remained operational, producing over 40 percent of Swiss electricity in the 1990s and nearly rivaling hydropower as the nation's dominant power source.[27]

Belgium's utilities were also successful in pushing ahead with nuclear construction, in spite of growing skepticism from the general public and the government. By 1985, seven large reactors had been put into operation at the Doel NPP near Antwerp and the Tihange NPP in Wallonia. Following Chernobyl, it was decided not to proceed with the construction of a proposed fourth unit at Doel. But the reactors that were already operational were left untouched, and for a few years in the mid-1980s they produced a staggering two-thirds of Belgian electricity. In 1999, however, the Belgian government announced that the operating lifetime of the country's reactors would be limited to forty years. Along with a ban on new reactor construction issued in January 2003, this decision seemed to indicate that the Belgian atomic age was coming to an end.[28]

In contrast to Belgium, the Netherlands never came to rely heavily on nuclear power as an energy source. This was closely linked to its huge domestic reserves of natural gas, which seemed to offer a safer and more affordable way to generate electricity. Nevertheless, there were many nuclear proponents in the country, and in 1974 a tough parliamentary battle over the country's nuclear future commenced. Apart from the proposed construction of new nuclear power plants, the debate was influenced by Urenco's uranium enrichment plant in Almelo, which critics portrayed as a means of nuclear weapon proliferation and nuclear cooperation with nondemocratic nations in the Global South. In 1984 a government committee recommended keeping the country's two existing nuclear stations in operation but not building any new reactors. Following the Chernobyl

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disaster, the remaining political support for nuclear energy dwindled. In 1994, the Dutch parliament voted to close the country's only large-scale nuclear plant, the 452 MW Borssele NPP, by 2003. This decision would be reversed in the twenty-first century, as we will see. In the meantime, the Netherlands closed its 55 MW boiling water reactor at Dodewaard in 1997.[29]

Finland, finally, took four commercial reactors into operation from 1977 to 1982. Then nuclear construction stagnated. A group of utilities received a construction permit for a fifth reactor, but it was withdrawn as a consequence of the Chernobyl disaster. A few years later, the Finnish Parliament rejected another reactor proposal submitted by a consortium of companies. However, in 2003, parliament allowed TVO, which had already built two large Swedish-made BWRs at Olkiluoto on the Gulf of Bothnia, to proceed with a 1,600 MW European pressurized water reactor (EPR) at the same site.[30]

In summary, six Western European countries—Denmark, Norway, Ireland, Luxembourg, Portugal, and Greece—never embarked on large-scale nuclear construction, in spite of earlier plans to do so. Austria built a nuclear power plant but never allowed it to go online. Italy built and took into operation several reactors but closed all of them prematurely. In contrast, Germany, Belgium, the Netherlands, Spain, Switzerland, Sweden, and Finland invested heavily in the atom and managed to keep a large number of reactors operational, at least for the time being. Numerous planned reactors in the latter group of countries were canceled, and some reactors that were under construction were abandoned. In Germany and Sweden, political decisions were taken to phase out nuclear energy, and the German *Atomausstieg* would eventually be implemented. Yet the momentum of past commitments, combined with lower than expected electricity demand, allowed utilities in a number of countries to establish nuclear power—at least temporarily—as a significant contributor to the national electricity mix. The share of nuclear power was even higher in France, which forms an exceptional case to be discussed separately.

East Asia and Oceania

The Japanese nuclear industry worked hard to convince the general public that its reactors were safe and environmentally friendly. At the same time, the industry faced numerous delays in getting new nuclear power plants up and running, and operators struggled to come to grips with accidents and

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technical problems. By 1975, it was already clear to industry insiders that the goal of having 27,000 MW of nuclear capacity online by 1980 would not be met, and the target had to be lowered to 16,600 MW. JAEC's annual report blamed the slowdown on "the general rise of public concern about preservation of the environment and worries about nuclear power." Yet it admitted that these concerns had been "amplified by nuclear plant troubles here and outside [Japan] creating an extremely severe condition."[31]

The Chernobyl disaster strongly influenced Japanese public attitudes toward nuclear power. Concerns were raised about the national safety culture. It was revealed that information about the operational experiences of the nation's reactors had been deliberately concealed. Critics portrayed the nuclear industry as "inward looking and conservative." Then, the country fell into a long-lasting economic recession, causing electricity demand projections to be revised and making new nuclear projects less attractive investments. By the mid-1990s "a sense of unprecedented gloom" pervaded all things nuclear in Japan. The gloom was accentuated by a series of accidents, including a sodium coolant fire at the Monju prototype fast breeder in 1995, which led to its permanent shutdown, and two serious accidents at the Tokai reprocessing plant in 1997 and 1999. The latter resulted in radiation exposure of hundreds of employees and the deaths of two workers.[32]

The situation was more promising in neighboring South Korea. Korean nuclear expansion was allowed to continue unabated in spite of a public debate that was often fierce, reflecting the tremendous strength of South Korean techno-nationalism and nuclear power's broadly accepted role as a key contributor to the country's modernization. The environmental and health risks associated with nuclear power were considered much less significant than the risk of falling behind in global economic competition. As Sheila Jasanoff and Sang-Hyun Kim put it, "The fear of losing national autonomy, competitiveness and developmental steam largely overrode public concerns for physical safety."[33] Korea Electric Power (KEPCO, not to be confused with Japan's Kansai Electric Power) initiated construction of six large reactors in the course of the 1980s and nine more in the 1990s. From 1986 to 1993, the atom supplied more electricity to the state grid than any other energy source.[34]

In Taiwan, the focus of the nuclear debate was the island's fourth nuclear power plant, the Lungmen NPP, which was approved by the government in 1980. Lower than expected electricity demand growth meant that there

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was no pressing need to start construction immediately. Then, following the 1986 Chernobyl disaster, the public grew suspicious of the safety of the country's nuclear steam engines, and the Legislative Yuan voted to freeze Lungmen's budget. In what followed, Taiwan's nuclear future became deeply intertwined with the island's transition to democracy, as the emerging opposition party, the Democratic Progressive Party (DPP), took a decidedly antinuclear stance. Amid fierce controversy, the Lungmen NPP project was revived in the 1990s, and the first concrete was poured in March 1999.[35] The project grew increasingly contentious, one reason being that the Taiwanese Atomic Energy Council found numerous construction flaws and illegal design changes on the part of Taipower, the state utility. There were also fears that seawater could seep into the plant's foundations. Opposition to the project helped DPP candidate Chen Shui-bian win the 2000 presidential election, ending half a century of Kuomintang (KMT) rule in Taiwan. In spite of this, construction of the Lungmen NPP continued in the early twenty-first century. The two-reactor plant would eventually be completed, but the opponents got the last word: The reactors were never allowed to operate. Numerous macrolevel controversies, especially regarding nuclear waste management, accelerated the decline of Taiwan's nuclear program. Unable to move forward with new nuclear power plants, Taipower found it more appropriate to build coal-, oil-, and gas-fired plants to meet electricity demand.[36]

Further south in the Asia-Pacific region, Australia's planned nuclear power station at Jervis Bay sparked fierce debate. Doubts about the adequacy of the emergency core cooling system and climbing cost estimates led to the project's indefinite postponement. For some time, the enthusiasts continued to dream about a nuclear-powered Australia. In 1974, for example, a report by the Australian Mineral Development Laboratories recommended that Australia "aim for establishment of a great industrial complex based on a multiplicity of nuclear power stations and building of a 3,000–4,000-MW power station in South Australia concurrently with an enrichment plant." Such visions, however, turned out to be unrealistic. Rex Connor, Australia's controversial minister of minerals and energy, firmly opposed any revival of nuclear planning, citing numerous safety issues with existing reactors worldwide and the challenge of nuclear waste disposal. As a result, nuclear power never gained traction in Australia, despite the country's rich uranium resources.[37]

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New Zealand's plan to go nuclear likewise lost much of its appeal after a major natural gas find was made on Maui and new coal deposits were spotted. Building a natural gas plant was found to be much less expensive, less complex, and less risky than building a nuclear station, so the atomic vision faded. It was revived following the first oil price shock of 1973–1974, but opponents argued that a nuclear power plant in New Zealand would be unreasonably expensive and that it would tie the country to foreign suppliers of equipment and fuel. Another problem was that of nuclear waste disposal. Over the following years, antinuclear sentiments increased rapidly in New Zealand, influenced by the North American, West European, and Japanese nuclear controversies. Moreover, in 1978, a Royal Commission of Inquiry reported that "nuclear power is not justified for New Zealand until about the turn of the century, or even perhaps later." Consequently, the country's atomic plans fizzled out. Instead, New Zealand scaled up domestic fossil fuel production and invested in geothermal power.[38]

The Collapse of the Communist Atom

In the 1970s and 1980s, construction of numerous large reactors began in the Soviet Union and Central Europe, but many of them would never be completed. The Soviets encountered significant challenges in their efforts to develop reactor technologies, and they suffered from the inefficiencies of the country's centrally planned economy. Nuclear builders faced endless shortages of materials, and they were troubled by the low quality of many key components. Repeated accidents in operational plants worsened the situation further, culminating in the explosion of Chernobyl's fourth reactor in April 1986.

It is difficult to fully assess Chernobyl's impact on the Soviet nuclear industry, because the catastrophe meshed in complex ways with the economic, political, and cultural crisis the country faced in the second half of the 1980s. A heightened awareness of nuclear safety became intertwined with economic hardship, the political struggle for national independence in some union republics, and the Communist Party's loosening grip on society.

RBMK enthusiasts did what they could to save the Chernobyl-type nuclear stations that were still in operation or under construction. They were more successful at some sites than at others. Remarkably, they

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managed to keep the remaining three reactors at Chernobyl itself in operation despite the severe radioactive contamination at the site.[39] They also completed a third RBMK unit at Smolensk and a second unit at Ignalina in the Lithuanian SSR.

However, the construction of a third reactor at Ignalina stalled. It was 60 percent complete when the Chernobyl disaster occurred, after which it quickly became the main target of an emerging Lithuanian antinuclear movement. The critics pointed to Ignalina's problematic envirotechnical entanglements, arguing that Lake Drūkšiai, the source of the plant's cooling water, was too small to support any additional reactors. Opposition to the plant's expansion was further accentuated by the secrecy surrounding the Soviet plans for Ignalina's future. The nuclear debate at Ignalina subsequently morphed into a Lithuanian national liberation movement.[40]

Environmental protests broke out in the Volga basin, too. Construction of three large nuclear power plants—the Tatar, Bashkir, and Gorky NPPs—that would use the Volga and its tributaries for cooling was halted in 1990, and the sites were abandoned. As in the case of Ignalina, envirotechnical issues related to wet nuclear extractivism played a prominent role in these controversies. The Kostroma NPP further upstream on the Volga was also given up. With the notable exception of Balakovo, where the engineers managed to complete four of six planned VVER-1000 reactors, the vision of the Volga as a Soviet nuclear frontier failed to materialize.[41]

Crimea also evaded accession to the club of Soviet nuclear provinces. Construction of the Crimean NPP, which had begun in the late 1970s on the Sea of Azov, was stopped in Chernobyl's aftermath for a plethora of reasons. Setting aside the controversies surrounding the plant's complex cooling water arrangements, opponents pointed to seismic activity in the area. Politically, nobody was eager to support the project. For local residents, Crimea's status as a health and tourist destination did not go well with industrial development, as represented by the nuclear power plant. In the post-Soviet era the ruins of the Crimean NPP were transformed into a scenic recreational space where music festivals were held.[42]

Construction of the Volgodonsk (Rostov) NPP also stalled, for the time being. So did the preparatory work for new VVER-1000 plants outside Kharkiv, Minsk, and Odessa, which were intended to supply those cities with heat and electricity. By contrast, construction continued at Kalinin, where the Soviets managed to bring an additional VVER-1000 reactor

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online after the Chernobyl disaster. At the Zaporizhzhia site in Ukraine, an impressive five out of six planned VVER-1000 reactors were in operation by 1989, making this plant the largest of all nuclear power stations in the Soviet Union. Further west in the Ukrainian SSR, one of Rivne's two VVER-1000 reactors went into operation after the Chernobyl disaster but before the collapse of communism, as did the third reactor at the South Ukraine energy complex and a first reactor at Khmelnytskyi. Beginning in 1988, however, Ukrainian protests against the Khmelnytskyi NPP surged, eventually preventing the completion of the plant's second unit.[43]

Further south in the Soviet Union, the Armenian nuclear power plant, which had two VVER-440 reactors, was closed in 1989 in the aftermath of the Chernobyl disaster and the terrible Spitak earthquake. Meanwhile, at Mayak, the construction of the South Urals NPP, which included three fast breeders, was terminated in 1992 due to a lack of funds. The plant was then torn down. The efforts to install numerous heat-generating AST-500 reactors near major cities likewise came to an end. Only one such machine was ever commissioned, outside the city of Voronezh.[44]

Nuclear construction in Central Europe also stagnated in the post-Chernobyl period. In Poland, protests against the Żarnowiec NPP, which began to be erected on a lake near the Baltic Sea in 1982, became entangled with the struggle for democracy, and the project was eventually abandoned. Construction of four VVER-1000 reactors in Bulgaria, at Kozloduy and Belene, was delayed first by the Chernobyl disaster and then by the rise of a broader Bulgarian environmental and antinuclear movement. Mirroring the Lithuanian and Polish developments, the Bulgarian antinuclear protests soon turned into an outright anti-communist and anti-Soviet struggle. By 1989 "eighty percent of the equipment had been supplied and about forty percent of the first reactor had been completed" at the Belene site. But the facility never went online. Bulgaria's nuclear enthusiasts were more successful at Kozloduy, where four older VVER-440 reactors were already in operation. The engineers connected the first VVER-1000 unit (the site's fifth reactor) to the grid in 1987 and a second one in 1991.[45]

Hungary, East Germany, and Czechoslovakia also aimed to build VVER-1000 plants. In September 1986, Hungary began expanding its Paks NPP, hoping to add two VVER-1000 reactors to the four VVER-440 units that were already in operation at the site. However, construction stalled in the late 1980s. So did construction of East Germany's Stendal NPP, which was

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Figure 5.2
Ruins of the unfinished Stendal nuclear power plant, East Germany. *Source*: Photo by the author, May 2022.

under way on the Elbe near Magdeburg (figure 5.2). Another GDR plant that had been tentatively planned further upstream on the Elbe, near Dessau, was also shelved.[46]

In Czechoslovakia, the Mochovce and Temelín NPPs were severely delayed, first by the Chernobyl disaster and then by the collapse of communism and the partition of Czechoslovakia in 1992–1993. At Temelín, local authorities issued a license for construction of the main buildings just a few months after the Ukrainian catastrophe. Construction officially began in March 1987 but did not progress far before the Velvet Revolution of 1989. Amid fierce controversy, the first postsocialist Czechoslovak government, led by Václav Havel, allowed construction to continue in 1990, though it was decided to limit the number of reactors to two, instead of the planned four.[47] It would take another decade to complete the pair.

In addition to the abandonment of ongoing reactor construction, a number of operational reactors in the former Soviet Union and Eastern Europe were permanently closed. The first site to face this fate was Greifswald in East Germany. Its five operational VVER-440 blocks were taken

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offline immediately after Germany's reunification in 1990. Helmut Kohl's federal government was unwilling to fund the necessary safety upgrades to bring the reactors up to Western standards, and no private investor wanted to take over the massive plant.[48] The smaller Rheinsberg reactor was also closed. The shutdowns continued with the two RBMK reactors at Ignalina in Lithuania, the four old VVER-440 reactors at Kozloduy in Bulgaria, and two similar reactors at Bohunice in Slovakia. These plants were all considered too dangerous by Western observers, and the EU even made their closure a condition for Lithuania, Bulgaria, and Slovakia to join the European Union. Meanwhile Ukraine eventually closed the remaining three reactors at Chernobyl, the last of which was permanently shut down in December 2000.[49]

Disappointment in the Global South

In the Global South, nuclear power had long been hailed as a path to prosperity and modernity. Yet very few of the envisioned southern reactors were ever completed. Despite their eagerness to "go nuclear," most countries failed to launch a single nuclear power plant, and the extravagant programs of India, Iran, and Brazil could not be sustained. India was the most successful in terms of the number of reactors built, with ten in operation by the end of the 1990s. However, those ten reactors combined provided only 1,940 MW of electrical capacity, and their load factors hovered around 50–60 percent at best. This left nuclear power as a virtually insignificant energy source, far behind the fossil fuels.[50] Brazil had its Angra-1 reactor up and running by the end of the century, but that was it. Argentina, Mexico, and South Africa each took two reactors into operation. Iran, the Philippines, and Cuba made significant progress in constructing their first reactors but ultimately failed to complete them. Israel, Turkey, and the North African countries did not manage to go from plan to actual construction despite a strong urge to do so.[51] In Southeast Asia, the nuclear visions of Thailand, Indonesia, and Bangladesh came to nothing, as did those of Iraq, Kuwait, Chile, Colombia, Puerto Rico, Nigeria, and Ghana.

The high cost of nuclear power plants was by far the most important reason for these failures. The hybridization of nuclear science with steam and hydraulic engineering resulted in machines that were among the most expensive artifacts the world had ever seen. This did not align with the small budgets, fragile fiscal situations, lack of human resources, and political

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instability of many "developing" countries. Financing nuclear power plants with domestic capital was out of the question for most of them, and foreign credit was difficult to obtain. For good reason, international lenders did not trust that they would get their money back, because it was hard to judge whether a proposed plant would ever be completed and what the real costs would be. The World Bank cautioned the southern nations that international funding organizations were certainly not about to "risk finance" on economically uncertain nuclear projects just because nuclear power was "the thing to have."[52]

In most cases, the only realistic way to finance nuclear projects in the Global South was to have the governments of exporting nations—the United States, Canada, France, Germany, and the Soviet Union—back the southern projects with generous funding plans and state guarantees. State financial agencies such as the US Export-Import Bank and Canada's Export Development Corporation played central roles in this context.[53] Sooner or later, however, the importing countries would have to repay the resulting debt. Domestic opponents of nuclear energy balked at the costs, which threatened to blow deep holes in national budgets. They also worried about becoming financially dependent on the Global North.[54] Against this backdrop, many southern countries found it "easier to pay out relatively small sums annually for oil rather than try to raise large sums for a nuclear plant."[55]

Moreover, as in the Western world, the cost of nuclear construction steadily increased throughout the 1970s and 1980s. The Global South watched with unease as new regulatory requirements—formulated in response to accidents and new insights about reactor safety in operational Western plants—made nuclear power increasingly expensive in North America, Europe, and Japan. Since the Global South imported their reactors from the Global North, the cost escalations inevitably spread southward. For example, in 1978, the cost of Brazil's Angra-1 reactor, which was delivered by Westinghouse, was reported to have doubled from the original 1972 estimate of $600/kW. By 1984, the project had exceeded the initial budget of $300 million by approximately 400 percent, and the reactor was still not operational. The expected costs of Brazil's massive nuclear program with Germany rose even more dramatically. Before the Three Mile Island accident, they were already reported to have escalated from around $10 billion to $20–30 billion. This cost inflation sparked a growing antinuclear movement in Brazil in the late 1970s. In the case of the Philippines, the cost

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of the proposed Bataan NPP rose from US$500 million when negotiations began with Westinghouse in 1974 to US$1.1 billion when the contract was signed two years later. Critics expressed "contempt over the ballooned power plant cost."[56]

Cost escalations fueled opposition in Iran, too. Prime Minister Jamshid Amouzegar, an oilman who took office in August 1977 amid an economic recession, launched a commission of inquiry to assess "the real need" for the country's nuclear investments "considering the rising costs and risks" of the Shah's ambitious program. It was found that the cost of nuclear electricity from KWU's Bushehr NPP would be nearly three times higher than the average cost in other countries. The total costs of the project had risen from $3 billion to $7 billion. In October 1978 the Atomic Energy Organization of Iran (AEOI) announced plans to scale back its nuclear program, limiting it to the four German and French reactors that were already under construction. Shortly thereafter, with the advent of the Islamic Revolution, construction of these reactors was suspended as well.[57]

Overall, on the eve of Three Mile Island, nuclear power costs were seen to be "rising faster in developing countries than in the highly industrialized countries." A typical plant in the Global South cost between 70 and 100 percent more than comparable stations in the West.[58] An important underlying reason was the global nuclear industry's transition to very large reactors. As we have seen, this scale-up was interpreted as the only way for nuclear power to become competitive with fossil fuels. However, large reactors failed to meet the specific needs of developing countries. Beyond financial challenges, many developing countries simply had insufficient overall electricity demand. Very few had electricity grids capable of supporting the 1,000 or 1,300 MW machines that were becoming standard in the United States, Western Europe, East Asia, and the Soviet bloc.

The supplier countries sought to respond to this dilemma by elaborating on smaller reactors specifically designed for the Global South. As early as 1971, the International Atomic Energy Agency (IAEA) and a group of Western countries—the United States, Britain, Canada, West Germany, France, and Sweden—launched a "fact-finding project" with the aim to explore possible nuclear power plant sites in the Global South for reactors with a capacity of 100–160 MW. The idea was that such projects could be financed through development aid. In a separate move, France's Chantiers de l'Atlantique, a CEA licensee, developed a 125 MW PWR model that

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could be mounted on a barge and towed to one or the other developing country; the Philippines and Egypt were among the countries that were reportedly interested in this innovation. In the United States, meanwhile, vendors envisioned constructing small, largely prefabricated—or, as they would later be known, modular—reactors for export to the Global South. There was only one problem: small reactors were even more expensive per kilowatt than large reactors, and they were in no way competitive with available fossil fuel solutions. Unsurprisingly, then, the idea of building smaller stations in the Global South went nowhere.[59]

Costs aside, the developing countries worried about reactor safety. In May 1979, the All India Atomic Energy Employees Coordination Committee drew attention to "perilously high radiation levels" inside the Tarapur nuclear power plant. The radiation level was "so high that employees consider it a death trap." Other Indian plants struggled to come to grips with heavy-water leaks. DAE chairman Homi Sethna conceded that India, as a developing country, could not naturally be expected to meet the stringent safety standards formulated in the West. "To make equipment in India is a very difficult job," he explained, "because real industrialization of India is less than 20 years old. To jump from weaving of cloth to making sophisticated equipment—pumps with zero leaks and other things—is a difficult task."[60]

Additionally, the far-from-convincing track record of operational Western reactors made southern governments wary. Brazilian analysts noted, for example, that KWU, the German reactor vendor, faced problems with its Biblis A and B reactors, which came online on the Rhine in 1975 and 1977. They also observed that the planned Biblis C unit, intended as a model for the reactors to be exported to Brazil, had yet to be built. In other words, Brazil was buying an unproven design.[61] In the case of Argentina, where AECL was building the country's second reactor at Embalse, there was bad news from Canada in the spring of 1979: Previously unknown design flaws had been spotted in the Pickering NPP's steam generators. The same flaws were found in the four steam generators at Embalse, where they had to be corrected at substantial cost.[62] In Mexico, work on the Laguna Verde NPP was delayed due to the need for design modifications to General Electric's Mark II BWR reactors.[63] Unsurprisingly, the safety concerns in the Global South were heightened after the 1979 Three Mile Island accident. The Philippines, for example, feared that a similar accident could happen at the

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recently built Bataan plant because its PWR design resembled that of the failed Pennsylvanian facility. In a radical decision, the government then decided not to bring the Bataan reactor online.[64]

Reactor safety was often debated alongside mesolevel envirotechnical dilemmas. As in the West, nuclear power plants in the Global South would have to smoothly tap into regional water resources (for cooling and freshwater supply), cope with challenging soil and rock conditions, adapt to earthquake risks, and find acceptable forms of coexistence with agriculture, fisheries, tourism, and navigation. These challenges were considerable. In Brazil, for example, construction of the Angra I nuclear power plant "quickly ran into numerous ecological problems." A number of "logistical water issues" plagued the PWR project at its coastal site. There were construction delays due to excessive rain. The situation was not much better at the nearby Angra II construction site, where KWU was erecting its first Brazilian reactor. In September 1978, the German magazine *Der Spiegel* published a widely cited article reporting that the German-Brazilian deal was in jeopardy due to unforeseen engineering issues. As a result, the expected start-up date for the first KWU reactor was pushed back from 1986 to the 1990s. The reactor was finally connected to the grid in 2000.[65]

Israel planned to erect its first nuclear power plant in the Nitzanim area on the Mediterranean. The problem was that the proposed site was only 32 km south of Tel Aviv, in an area with several popular beaches. The prospect of having a potentially dangerous nuclear power plant there sparked public protest, especially after a large geological fissure was discovered near the proposed site. The project was also criticized by the country's Environmental Protection Service. As an alternative, Israel contemplated erecting a nuclear power plant on the coast of its occupied territories in Egypt. After the signing of the Israel-Egypt peace treaty in early 1979—by which time Sinai was no longer under Israeli control—this idea morphed into a possible joint nuclear plant with Egypt in the same region.[66] By building the plant as far away from its core territories as possible, or even abroad, Israel hoped to avoid any detrimental health or environmental consequences in the event of a nuclear disaster. But the plan was ultimately deemed politically infeasible, and the project never materialized.

The Philippines faced considerable envirotechnical challenges in selecting a suitable site for its Bataan NPP. The IAEA, which assisted the Philippines, initially recommended a site near Bagac on the South China Sea.

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Ebasco, a private firm that conducted a feasibility study for the project, deemed this location unsuitable due to the potential for devastating tidal waves. The site was therefore changed to Napot Point a few kilometers north. However, that site also proved problematic because of its proximity to an active volcano. This contributed to the decision to abandon the project after Three Mile Island.[67]

Finally, a major reason behind the Global South's failure to develop nuclear power was the obstacles many countries faced when trying to forge a nuclear circular economy. As we have seen, many southern countries hoped to establish domestic nuclear fuel cycles that would be independent of the West. They wanted their own enrichment and reprocessing plants. After India's "peaceful" nuclear explosion in May 1974, this became impossible. As discussed in chapter 3, fuel cycle technologies were, from now on, interpreted primarily as potential pathways to an atomic bomb rather than as helpful tools in the pursuit of civilian nuclear power. Initially, the supplier countries—the United States, Canada, France, and Germany—demanded that the export of fuel-cycle technologies be combined with strict safeguard arrangements. Next, the United States adopted an even stricter nonproliferation policy, viewing virtually all nuclear exports as undesirable, even those covered by well-elaborated safeguard agreements. The Americans put pressure on Canada, France, and Germany to follow suit. Faced with the prospect of nuclear programs that would lock the Global South into long-term dependence on Western nuclear fuel cycle services, the allure of nuclear power as a path to modernity, prosperity, and freedom lost much of its political appeal in the developing world.

The French Exception

A few countries defied the global stagnation, establishing nuclear power as a dominant source of electricity. In Western Europe, Belgium reached an impressive 67 percent nuclear share in 1986, while Sweden's nuclear contribution peaked at 53 percent in 1996. Switzerland, Spain, and Finland also achieved high nuclear power shares. Outside the Western world, Hungary, South Korea, Taiwan, and Japan made nuclear power a dominant electricity source, with the atom's contribution peaking at 48 percent in 1990, 49 percent in 1987, 52 percent in 1985, and 31 percent in 1998, respectively. Afterward, these countries' reliance on nuclear power began

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to decline. Following the end of the Cold War and the dissolution of the Soviet Union, Yugoslavia, and Czechoslovakia, several "new" nations also became heavily dependent on nuclear power, including Lithuania, Ukraine, Armenia, Slovakia, and Slovenia. Upon becoming independent in 1991, Lithuania produced more electricity from its two Chernobyl-type RBMK reactors than it could consume domestically. However, by 2005, the two units had been permanently shut down, and nuclear power's contribution to the country's electricity mix dropped to zero.[68]

The most striking exception from the overall global pattern, however, was France. It reached a 79 percent share of nuclear electricity in 1993. No other country, and especially no other large nation, ever came close to that figure. Undeterred by antinuclear activism, scientific and economic criticism, and the Three Mile Island and Chernobyl accidents, the state-owned utility EDF and the government enforced their "all-nuclear" policy.

This did not mean that there was no opposition to nuclear power in France, nor that the French nuclear industry developed without problems. The Messmer Plan, in particular, was widely debated among both the general public and the scientific community. Scientists and engineers criticized the government's policy not only for its one-sided focus on the atom, but also for its decision to rely on light-water reactors. Like the British, many French experts considered these reactors to be unsafe. They emphasized that the light-water reactor was an American invention and that France, as of the mid-1970s, did not yet have much experience with this type of reactor. They doubted that the technology could be trusted.[69] Inspections of the French nuclear industry organized by the Corps des Mines seemed to confirm these doubts. Siegfried Evens, who has studied the history of French nuclear safety extensively, writes that the inspectors "were frustrated about how the 'nuclear boilers' were constructed." They noted dryly that the pressure vessels should be constructed "with more care." They were utterly critical of Framatome, the company set up to facilitate the transfer of Westinghouse's PWR technology to Europe, as well as the Creusot Loire factory in Chalon-sur-Saône, where steam technologies had been manufactured long before the nuclear era.[70] Overall, there was a considerable lack of trust between the main players in the French nuclear industry.

There was also a fierce debate about the envirotechnical dilemmas associated with French nuclear construction. Jacques Belle, a former advisor to Environment Minister Robert Poujade, accused EDF of pushing through its

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massive nuclear power program without considering the mesolevel problem of "probable local climatic changes, especially in the Rhône and Loire River valleys." Belle called for a moratorium on nuclear construction there and at several other "sensitive sites," including the Gironde estuary and the Mediterranean coast. The French Ministry of Culture, for its part, disliked the construction of cooling towers in the country's famed wine landscapes. There were fears that the ecosystems of the Loire and Rhône would face "total suffocation" if EDF's plans were carried out. Macrolevel concerns about the supply of nuclear fuel became another argument against the atom. Critics claimed that nuclear power could "not ensure the energy independence of France because of the limited character of the national uranium resources." In 1975 hundreds of scientists joined with trade unions, local authorities, and environmentalists to condemn the accelerating nuclear program.[71]

In 1976 and 1977, however, the state took decisive steps to stifle criticism and eliminate alternative energy strategies. In July 1977, antinuclear groups occupied the Superphénix fast breeder construction site. The CRS, a special police force, "moved to clear the site with brutal efficiency, using tear gas and concussion grenades. One person was killed and five were seriously wounded. More than one hundred suffered gashes or other minor injuries." After this trauma, the antinuclear activists, who were increasingly treated as traitors and criminals, moved away from site occupations as a tactic.[72] EDF and the Ministry of Industry also effectively countered critical CEA safety engineers and a skeptical Finance Committee of the National Assembly, which strongly criticized the size of the nation's nuclear program and the cost of nuclear energy compared to coal. In the end, even the most controversial components of France's nuclear program remained in place, including the UP3 extension of the La Hague reprocessing plant and the Superphénix fast breeder project. In 1980, the year after Three Mile Island, EDF initiated construction of no less than six new reactors. From 1981 to 1985 the utility launched eleven more projects. Construction of the last two reactors, at Civaux, began in the aftermath of Chernobyl. By that time, no other reactors were being initiated anywhere in Europe.[73]

Overall, nuclear power's rise to prominence in France can be attributed to a highly centralized, military-like government apparatus, including a brutally efficient police force; a single, state-owned electricity company not exposed to open market competition; and a severe lack of domestic fossil fuels combined with an existential urge to attain energy independence. In

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addition, civilian nuclear investment went hand in hand with the nation's nuclear weapons status. However, France's astonishing achievement was also facilitated by the successful standardization of French-American pressurized water reactors (PWRs), which allowed EDF to reap economies of scale in a way that few other nations proved capable of doing. Concentrating multiple nuclear steam engines in large reactor parks, such as the one at Gravelines on the English Channel with its six large reactors, functioned in the same way. This allowed the French nuclear industry to partly resist the global cost escalation in nuclear construction.[74] Later on, South Korea and China would seek to emulate that pattern. In the French case, however, there was a "gradual erosion of EDF's determination to standardize" because regulators forced builders to introduce numerous design changes, especially for the last few reactors (referred to as the N4 series). This arguably paved the way for the demise of the French success model, as evidenced by lengthened construction times and cost escalation toward the end of the program.[75]

Conclusion

If there ever was a "golden age" of nuclear power, it was brief. The second half of the 1960s saw a surge in commercial reactor construction in many parts of the world. This was based on the perception that nuclear power had become competitive with coal and oil, as well as on the expectation that any problems related to reactor safety, envirotechnical issues, and the challenges of the nuclear fuel cycle could be satisfactorily addressed. The 1973–1974 oil crisis further boosted worldwide nuclear planning and raised expectations to an all-time high. Yet just a few years later, the nuclear industry headed for stagnation and decline. National nuclear programs were scaled back, and numerous planned reactor projects were canceled. Countries that had hesitated to invest in large-scale nuclear plants eventually decided against doing so. In some cases, fully completed nuclear power plants—notably Austria's Zwentendorf reactor, Germany's Kalkar fast breeder, Taiwan's controversial Lungmen plant, and the Philippines's Bataan NPP—were abandoned before being taken into operation. Many more were left half-finished as industrial ruins after construction was halted. Over time, numerous operational plants began to be decommissioned. As a result, nuclear power never became the dominant energy source that the visionaries of the 1950s and 1960s had anticipated. Nuclear energy's share

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in the global electricity mix eventually peaked at 17 percent in the mid-1990s and then began to decline.

France and a few other countries did manage to make nuclear power their primary source of electricity, demonstrating that it was not impossible to do so. Elsewhere, however, governments and utilities were overwhelmed by the challenges brought by nuclear science's "three marriages." And so, a vast majority of the world's nations ended up relying primarily—and often entirely—on nonnuclear energy sources for their electricity supply. Even in Western Europe, where enthusiasm about nuclear power's potential had been omnipresent in the early 1970s, many countries ultimately did not build any nuclear power plants. Others built one or a few reactors but no more. The United Kingdom and Germany reached fairly high nuclear shares, 28 percent and 31 percent, respectively, both in 1997. But then nuclear power's contribution gradually declined in both countries as reactors were shut down without being replaced by new ones. In the United States, Canada, and the Soviet Union, nuclear energy never surpassed 20 percent of the electricity mix.

Perhaps the greatest disappointment was the Global South's failure to harness the potential of the atom. A small group of countries, including Pakistan, South Africa, Brazil, Mexico, and Argentina, managed to take into operation one or two reactors. But then their nuclear investment stagnated and utilities turned to alternative fuels. India had an ambitious nuclear program and commissioned several modestly sized civilian reactors. However, these reactors contributed only marginally to overall electricity production. Chile, Indonesia, Bangladesh, Thailand, the Philippines, Egypt, Libya, Israel, Turkey, and Iran all had high hopes for nuclear energy in the 1970s but saw their programs fail.

Lower than expected growth in electricity demand went hand in hand with the global stagnation. When governments and utilities abandoned overly ambitious nuclear programs and planned reactor projects, they often cited revised projections of electricity needs as an underlying reason. The overall impression is that the actors were relieved by such downward corrections, precisely because they provided a convenient way to reduce investment in a problematic technology. By the late 1980s, global nuclear construction had all but collapsed. Whenever new generating capacity was needed thereafter, the choice fell almost exclusively on nonnuclear options, such as coal, gas, or renewables.

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6 The Renaissance That Wasn't

Many nuclear boosters interpreted the global stagnation of nuclear power as a temporary phenomenon that would soon give way to renewed growth. Before the 1986 Chernobyl disaster, prominent visionaries such as Alvin Weinberg had already prophesized that a "second nuclear era" was inevitable and that the world could look forward to a "nuclear renaissance."[1] Such expectations grew more pronounced during the following decades. Several seemingly plausible arguments backed up the new optimism, ranging from the urgent need to phase out fossil fuels in an age of climate change to the assertion that a new generation of reactors would make nuclear power inherently safe.

During the first decades of the twenty-first century, nuclear boosters were remarkably successful in garnering public and political support for their visions. Yet it proved difficult to turn the idea of a nuclear renaissance into a tangible reality. Very few new reactors were built worldwide in the new millennium. At the same time, older ones nearing the end of their operational lives were shut down. As a result, the share of nuclear energy in the global electricity mix was cut in half during the first quarter of the twenty-first century (figure 6.1). To understand this outcome, we need to examine not only the political twists and turns surrounding nuclear power but also how the atom's expected revival clashed with the features of the nuclear steam engine, its envirotechnical entanglements, and a multitude of problems linked to the nuclear fuel cycle.

Nuclear Newspeak

Following the Chernobyl disaster, nuclear visionaries around the world pondered how to regain public and political acceptance of the atom. They

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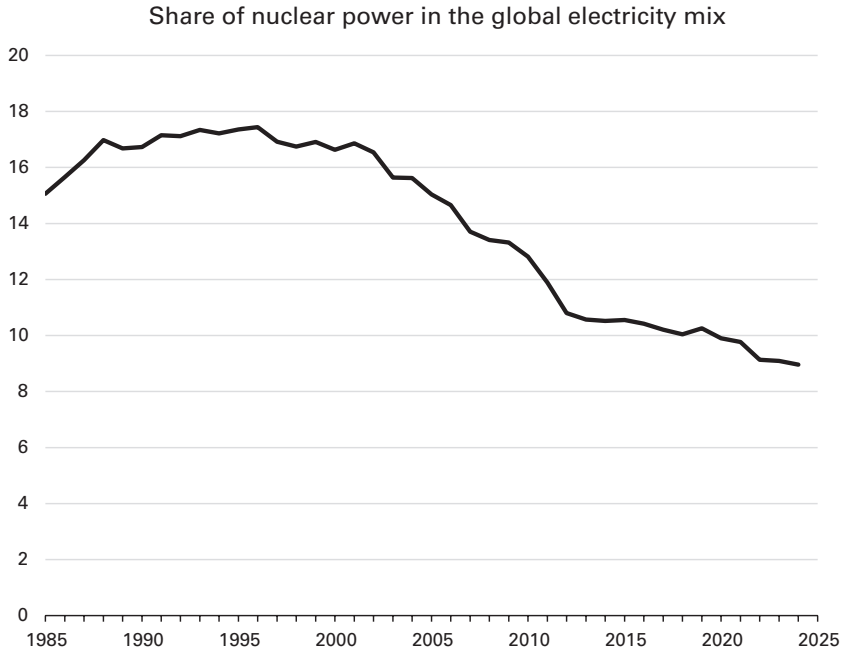

Figure 6.1
The share of nuclear power in the global electricity mix, 1985–2024 (percent). *Source*: Author's own graph based on data from Hannah Ritchie and Pablo Rosado, "Electricity Mix," 2025, https://ourworldindata.org/electricity-mix.

adopted four key strategies. First, they rebranded nuclear power as a sustainable, climate-friendly, low-carbon energy source. This occurred alongside the increased prominence of environmental issues in national and international political debates during the second half of the 1980s. In 1987 the World Commission on Environment and Development, led by Gro Harlem Brundtland, published *Our Common Future*, which established "sustainable development" as a key concept in environmental and economic policy. Then, in 1988, the United Nations set up the Intergovernmental Panel on Climate Change (IPCC). Soon after, at the fourteenth World Energy Conference, held in Montreal in 1989, the French delegation presented investment in nuclear power as "a duty of industrialized states to protect the atmosphere."[2] In the following years, especially after the Kyoto Protocol was signed in 1997, this interpretation of the atom as a savior of the global climate grew increasingly pronounced. The environmental and health risks of nuclear accidents

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and the dangers of radioactivity receded into the background of the public debate because they were perceived as a lesser evil than the existential threat of a warming world.

A second strategy began to take shape in 1999. That year, after a long period of decline, the price of oil finally turned upward when OPEC decided to reduce crude oil production. The oil price doubled in a short period of time, leading to renewed fears that fossil fuels might become scarce and difficult to access.[3] During the first decade of the new millennium, the oil price continued to rise, eventually reaching a dramatic peak in July 2008. Meanwhile, the Second Gulf War (2003–2011) reminded the industrialized world of the geopolitical dilemmas associated with oil dependence. And in Europe, concerns grew over the reliability of Russian natural gas supplies following dramatic supply disruptions in 2006 and 2009. These developments allowed the atomic enthusiasts to argue that nuclear power was a preferable energy source, because it was much less susceptible to market volatility and geopolitical conflict than oil and gas.

A third discursive strategy emphasized that nuclear safety had improved. During the first decade of the twenty-first century, optimism grew that a nuclear disaster would never happen again. The Three Mile Island and Chernobyl accidents were increasingly interpreted as inevitable childhood diseases in the progress of nuclear technology. Moreover, the accidents allowed the engineers to better understand the nature of nuclear risk and, consequently, to manage them more effectively. From this point of view, Three Mile Island and Chernobyl had a positive side; they were real-world failures from which much could be learned, and they opened the door to improvement. The nuclear engineering community seemed to embrace the philosophy of Plutarch: "To make no mistakes is not in the power of man; but from their errors and mistakes the wise and good learn wisdom for the future."[4]

The fourth and final strategy was to develop a new language and terminology for all things nuclear. Alternative terms were introduced to describe sensitive or controversial topics. For example, fast breeder reactors, which many people associated with technological failure and a dangerous plutonium economy, began to be referred to as "sodium-cooled reactors." Other new catchwords included the reassuring notions of "inherently safe" and "proliferation-resistant" nuclear technologies. Most twenty-first century nuclear visionaries avoided the term "plutonium," although they were keen

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to revive older dreams of a nuclear circular economy in which this chemical element was expected to play a central role. Similarly, they abstained from talking about "reprocessing." Instead, they discussed developing "advanced fuel-cycle technologies" and the possibilities linked to the "transmutation" of dangerous isotopes.[5]

An intriguing discursive shift was the reinterpretation of historical and future "reactor generations." Back in the 1950s and 1960s, visionaries had imagined nuclear energy progressing through three generations. The first included all "thermal" reactors, including light-water reactors (PWRs and BWRs), heavy-water reactors, and gas-cooled reactors. The second generation featured fast breeder reactors and high-temperature reactors, while the third generation centered on fusion reactors.[6] In the twenty-first century these generations were reshuffled. Fusion, while still of interest, began to be seen as a separate field from nuclear energy proper and was removed from the list. Breeders and high-temperature reactors were reclassified as belonging to a new "generation IV," and existing thermal reactors were grouped into "generation II." A new "generation I" was invented retroactively to denote the early pilot projects of the 1950s and early 1960s. The latest thermal reactor models, including the advanced boiling water reactor (ABWR) promoted by GE Hitachi and Toshiba, the Korean APR-1400 model, the European pressurized water reactor (EPR), Westinghouse's AP1000, and a few others were promoted to a new "generation III" and "generation III+."[7] In other words, the thermal reactors, which were traditionally considered a single generation of electricity-producing reactors, were now seen as representing three distinct generations. In this way, the nuclear industry sought to avoid the impression that the world's operational reactors were old and primitive, as they all (except for a few breeders) relied on thermal neutrons. Half a century after the inauguration of civilian nuclear power, it would have been too disappointing to view the hundreds of reactors in operation or under construction worldwide as belonging to generation I.

The Discursive Nuclear Renaissance

The rebranding of nuclear energy as climate friendly, reliable, and disaster free was successful in the sense that both governments and the general public began to view nuclear energy as a suitable and indispensable part of the world's future electricity mix, rather than as yesterday's failed

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technology. The first decade of the new millennium saw the rise of pronuclear policies worldwide. Numerous countries expressed new commitment and support for nuclear energy. The most strongly pronuclear governments included those of the United States, the United Kingdom, France, Russia, China, India, Japan, and South Korea. Finland and several of the former communist countries in Central and Eastern Europe were also enthusiastic supporters. In contrast, the nuclear policies of Germany, Switzerland, Belgium, Spain, and a few other West European countries were more hesitant. However, even in these countries, there was an underlying trend toward a more positive stance. Most notably, several countries that had decided to halt further nuclear expansion—or even close existing plants—in the years following Chernobyl opted to reverse these decisions.

In the United States, government support for the nuclear industry increased during the George W. Bush presidency (2001–2008). Washington had pursued a restrictive nuclear energy policy for over two decades. The Bush administration thought the time ripe to change this and decided to support the nuclear industry in several ways. These included renewed attention to developing a nuclear circular economy, as well as researching new reactor types and fuel cycle technologies. The Energy Policy Act of 2005, which passed both the Senate and House of Representatives with about 70 percent approval, was instrumental in this context. The act provided support for nuclear technology development through production tax credits, federal risk insurance to cover regulatory delays, federal loan guarantees, and nuclear liability protection. This spurred the nation's utilities to apply for permits to build no fewer than twenty-eight new reactors. A few years later, the Obama administration reaffirmed Washington's commitment to nuclear expansion, calling for "a new generation of safe, clean nuclear power plants in this country."[8]

The United States became proactive in international fuel cycle and R&D activities, too. Among other things, the Americans established the Generation IV Forum (GIF) and the Global Nuclear Energy Partnership (GNEP) as platforms for international cooperation among countries willing to embrace nuclear energy. GIF, established in 2001, focused mainly on generation IV reactor designs that would be deployed from around 2030. By late 2007, twelve countries and Euratom had signed the GIF charter.[9] GNEP, launched in 2006, focused on promoting a closed nuclear fuel cycle. The spirit of both programs was strikingly reminiscent of the 1950s in their

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extremely optimistic outlook on the future of nuclear power, both nationally and globally.[10]

Meanwhile, the United Kingdom undertook a review of its energy policy. In May 2006, Prime Minister Tony Blair argued that the country needed "to put nuclear back on the agenda with a vengeance." The pronuclear stance of the Labour government—contrasting with social democratic antinuclear sentiments in countries such as Germany, Spain, and Sweden—was further strengthened under Blair's successor, Gordon Brown. In July 2007, Brown confirmed the government's view that "the security of our energy supply is best safeguarded by building a new generation of nuclear power stations." Over the next few years, British and overseas investors began planning new large-scale reactor projects at no fewer than seven sites: Hinkley Point, Sizewell, Bradwell, Wylfa, Oldbury, Sellafield, and Moorside.[11]

France was unique among large countries in its near-total dependence on nuclear power for electricity. EDF, the state-owned electricity company, operated fifty-eight reactors at the turn of the millennium. As many of these reactors were approaching the end of their planned operating lives, EDF pursued a government-backed strategy to replace them with approximately forty new generation III+ reactors. Construction of the first began at Flamanville in 2007.[12]

In Italy, one of the first things Silvio Berlusconi's new populist government did when it took office in May 2008 was to announce a new nuclear expansion program. It set a target of having 25 percent of electricity come from nuclear power by 2030. The Minister of Economic Development called the decision to close all nuclear power plants in Italy after Chernobyl a "terrible mistake."[13]

The Netherlands was another country where a previous decommissioning decision was overturned. The country's only remaining nuclear reactor, located in Borssele on the North Sea coast, was scheduled to retire in 2003. However, its closure was first postponed to 2013, and then the decision to phase out the reactor was abandoned altogether in 2005. In 2006, the responsible utility and the Dutch government signed an agreement to continue operating the plant until 2033.[14]

Finland, meanwhile, had always been open to nuclear power. The country operated four large reactors since the early 1980s, and there was a strong political consensus on the need for additional nuclear capacity. Even the Green Party was supportive. In 2003, TVO, which already ran two large

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reactors at Olkiluoto on the Gulf of Bothnia, began construction of the country's fifth reactor at the same site. Nuclear expansion was politically conditioned by advances in spent fuel and waste management. This motivated Finland to become very active in this field. Eventually, it became the first country in the world to start construction of a deep repository for spent nuclear fuel.[15]

Further east, the Russian government presented a formal energy strategy in 2003 that placed nuclear power firmly at the center. The strategy stated that a significant portion of the expected increase in electricity usage by 2020 would need to come from nuclear fission. The Kremlin planned to double installed nuclear capacity during this period. Although no formal rationale was provided, a common interpretation was that Russia wanted to increase its use of nuclear power because it wished to conserve its oil and gas resources, which generated much of the country's export income. The Russian nuclear energy policy included a clear commitment to a closed nuclear fuel cycle, with reprocessing as a key component.[16]

China and India also had far-reaching nuclear ambitions. China's nuclear expansion had been rather hesitant in the 1980s and 1990s. Premier Li Peng's published journal reveals that nuclear expansion was not uncontroversial among top policymakers at that time. The next administration, led by Zhu Rong-Ji (1998–2003) also displayed "a high level of caution." However, from mid-2005 onward, with the preparation of the eleventh five-year plan, Beijing committed itself to rapid nuclear expansion. The government announced its intention to increase nuclear generating capacity to 70–80 GW by 2020, 200 GW by 2030, and 400–500 GW by 2050—roughly equivalent to the total installed capacity worldwide in the early twenty-first century! In addition to reactors, the Chinese government launched numerous fuel cycle projects. In 2006 it initiated the construction of a pilot reprocessing plant using the PUREX process at the Lanzhou Nuclear Fuel Complex in Gansu Province. The following year, China National Nuclear Corporation (CNNC), the country's primary nuclear builder and operator, signed an agreement with Areva, a French nuclear conglomerate formed in 2001 through the merger of Framatome, COGEMA, and Technicatome, "to assess the feasibility of a reprocessing plant for used fuel and a mixed-oxide (MOX) fuel fabrication plant in China."[17]

India was in a more difficult position at the turn of the millennium following the global outcry over its (and Pakistan's) nuclear weapons tests in

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May 1998. The country was subject to sanctions that made accessing foreign nuclear technologies and materials extremely difficult. But then the scene shifted. After the 9/11 terrorist attacks in the United States, the Bush administration began to forge closer strategic ties with India. In 2005, Washington announced its encouragement of full cooperation with India in civilian nuclear matters. Three years later a bilateral US-Indian nuclear deal was signed. This paved the way for a new era of Indian nuclear expansionism. New Delhi hoped to build as much as 63 GW of nuclear power by 2032.[18]

Lastly, Japan continued to promote nuclear power. Despite repeated accidents, delays, and scandals, the government vigorously pursued nuclear expansion. A plan to reduce the country's climate footprint, unveiled in 2008, aimed for "60–80 percent cuts in GHG emissions by 2050." Nuclear power was hailed as a key instrument to achieving this goal. The government stated that by 2020, nuclear power would supply 40 percent of Japan's electricity, rising to 53 percent in the longer term. South Korea also continued its expansive nuclear policy, aiming to increase the share of nuclear power in the country's electricity mix to 41 percent by 2030.[19]

Fukushima and the Cost-Complexity Trap

The new pronuclear policies paved the way for a significant number of reactors to start construction in the early twenty-first century. The year 2010 saw a total of sixteen new construction starts worldwide, a new record in the post-Chernobyl era. While not as pronounced as during the heyday of global nuclear development around 1970, when up to forty-three new reactors began construction in a single year, the expansion raised hopes that the much-heralded "nuclear renaissance" was underway.

In the course of the 2010s, however, the expansion stagnated almost everywhere, and the peak in new construction starts of 2010 was never reached again. Many reactor projects ran into unexpected obstacles, and a large number of planned projects were ultimately abandoned or postponed indefinitely. In the meantime, more and more operational nuclear power plants were closed and decommissioned. As a result, by 2024 the share of nuclear energy in the world's electricity mix had declined to 9 percent, roughly half of its all-time high of 17 percent in 1996.[20]

One reason behind this negative development was the Fukushima disaster of March 11, 2011. On that day, Japan experienced one of the worst

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earthquakes ever recorded. The epicenter was located seventy-two kilometers east of Honshu Island. The earthquake generated a massive tsunami that wrought terrible destruction along Japan's Pacific coast, where several large nuclear power plants had been erected in the preceding decades. One of them was the Fukushima Daiichi NPP, which consisted of six boiling water reactors. The tsunami flooded the plant and "disabled all diesel generators at the four oldest units, as well as electrical switchgear and cooling pumps, in what is known as a common cause event that takes out multiple safety systems and nullifies the careful redundancy designed into them." The result was catastrophic: "Unit 1's secondary containment building exploded from leaking hydrogen. Unit 3 followed two days later, Unit 4 the day after. Unit 2 did not explode, it burned. Core meltdowns occurred at Units 1–3."[21]

The disaster dramatically highlighted nuclear power's envirotechnical entanglements.[22] Never before had the vulnerability of a nuclear station to natural events, such as flooding, been so clearly demonstrated. Unsurprisingly, antinuclear sentiments grew in the tragedy's aftermath, not only in Asia but also around the world. Many governments reconsidered their earlier pronuclear policies or found that their hesitation about a possible nuclear revival was warranted. In Germany, where a long-term plan to phase out nuclear power had been established in 2000, Angela Merkel's government had just agreed to extend the operational life of the country's remaining reactors. That policy was quickly nullified after the Fukushima disaster as hundreds of thousands of people took to the streets in Berlin and other cities. In response to this new wave of antinuclear activity, the government promptly and radically ordered the immediate closure of the nation's eight oldest reactors. It then drafted new legislation mandating the retirement of the last German stations by 2022.[23] The Swiss government made a similar decision, stating that no new nuclear power plants would ever be built in Switzerland and that existing ones would gradually be phased out.[24] In Italy, the Fukushima disaster led to another national referendum, in which an overwhelming majority rejected the government's nuclear renaissance plan. In Belgium, tentative pronuclear proposals also came to a halt when political parties negotiating to form a new government agreed to implement the 2003 nuclear phase-out law, which provided for the closure of three reactors by 2015 and the rest by 2025.[25] Other countries did not make any immediate decisions to close reactors, but public opinion turned more antinuclear almost everywhere.

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Yet the Fukushima disaster was in no way the only reason behind the failure of the nuclear renaissance. However exceptional and dramatic the Japanese tragedy may seem at first, it was not an isolated event in global nuclear affairs. Rather, it was one of many interconnected developments that collectively signaled a deeper crisis for nuclear power as an energy source in the twenty-first century.

The most difficult aspect of that crisis had to do with the escalating costs of building and operating nuclear power plants. These cost increases reflected what I have earlier referred to as a cost-complexity trap: a long-term process in which the continuous discovery of new problems and risks in nuclear engineering leads to new regulatory requirements, which force operators to add new expensive components to an already complex technology. The cost-complexity trap had been a harsh reality for the nuclear industry ever since nuclear power's commercial breakthrough in the 1960s. In the twenty-first century, it continued to make nuclear plants ever more complex and costly. For example, the events of 9/11, which "demonstrated that the risk of terrorist attacks and sabotage might come from unimagined and unquantifiable sources," alerted nuclear regulators to new crisis scenarios that called for adjustments to safety arrangements.[26] Another trend pointing in the same direction was the increased occurrence of violent storms, hurricanes, and wildfires in an age of climate change. Such events were interpreted as having the potential to disrupt electricity connections, jeopardize cooling water intake and discharge, and block road access to nuclear stations in emergency situations. Other potential events that regulators began to interpret as threats in the twenty-first century included large oil spills or algal blooms in bodies of water from which the cooling water was sourced.[27]

The Fukushima disaster revealed additional vulnerabilities. In particular, it highlighted the risk of an extended loss of the external electricity supply combined with a failure of the emergency diesel generators, which could endanger the cooling of the reactors and potentially lead to a core meltdown. The tsunami also served as a reminder that the "ultimate heat sink"—that is, the sea, lake, or river from which a reactor draws its cooling water—could behave in unexpected and unreliable ways.[28] These insights called for costly backfits of operational nuclear power plants in many countries and redesigns of those that were in the planning or construction stage. By late 2011, the International Energy Agency warned that "financing for

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new [nuclear] projects might dry up in the face of mounting regulatory burden and longer lead times for construction."[29]

The cost-complexity trap hit Western Europe and North America the hardest. Here, electric utilities and equipment suppliers had not built new nuclear power plants in decades. They had no recent experience to draw on and found the task overwhelming. Industry players found that costly construction errors were likely and that meeting high quality standards was difficult. Consequently, all new reactor projects that made it past the planning stage faced multiyear delays and dramatic cost overruns. The cost of France's Flamanville-3 reactor increased fourfold to 13.2 billion euros, and its start-up was delayed by eleven years. Finland's Olkiluoto-3 reactor was originally expected to cost 3 billion euros, but the final cost was around 10 billion euros. Startup was delayed by fourteen years.[30] In the United States, the plan was to have two new reactors at the Vogtle NPP in commercial operation by 2016 and 2017, with an expected cost of US$14 billion. In reality, the last reactor did not become operational until 2024. By that time, Georgia Power estimated that the total cost of the project had exceeded US$30 billion. The construction of two new reactors at the Virgil C. Summer NPP in South Carolina was suspended due to similarly spiraling costs. The cost escalations in South Carolina were so dramatic that Westinghouse, the main contractor, filed for Chapter 11 bankruptcy protection in March 2017.[31]

The seemingly unstoppable increase in nuclear construction costs was concerning, especially considering the opposite trends in fossil fuels and renewable energy. The American shale gas industry experienced a breakthrough in the 2010s, which led to a revolution in US gas supply and paved the way for abundant, low-priced gas. This revolution posed an almost insurmountable problem for the US nuclear industry. It also had global repercussions: Liquefied natural gas (LNG) shipments previously destined for US ports had to be sold elsewhere. In addition, the abundance of shale gas reduced the competitiveness of coal in the United States, spurring exports of US coal to Western Europe and elsewhere. This resulted in lower fossil fuel and electricity prices in many parts of the world. Meanwhile, investment in renewable energy sources soared. Technical improvements and economies of scale in production, combined with strong government support in many countries, led to plummeting costs of wind turbines and

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solar panels. Since 2021, wind and solar power have supplied more electricity than nuclear reactors worldwide.[32]

A related trend that hindered the revival of nuclear power was the deregulation of electricity supply, which was particularly prevalent in the Western world. Traditionally, electricity markets were strictly regulated. There was little competition between suppliers, and electricity prices were predictable and even plannable. These conditions promoted long-term thinking, making even the most expensive power plant projects appealing to investors because there was a guaranteed market that ensured a stable return on investment. The situation changed radically when electricity supply was deregulated in the 1990s and early 2000s. From then on, utilities could no longer set electricity prices based on costs incurred. Instead, prices were determined by supply and demand. This resulted in less predictable prices and a more volatile market with significant daily and long-term fluctuations. In a deregulated marketplace, it became impossible to predict next month's electricity prices, let alone those in the following year or five years. Such a market did not align well with nuclear investment, which depended on long-term planning.

The combined effects of rising nuclear construction costs; increased competition from natural gas, coal, and renewables; and the deregulation of electricity caused utilities and investors to shy away from new nuclear power plants. By the 2010s, it had become nearly impossible to launch new nuclear projects in Europe and North America, regardless of government or public support for the atom. The only way to make "new nuclear build" economically feasible was to bypass the free market, such as by demanding government subsidies.[33]

The new economics of nuclear energy affected operational plants, too. The trend toward lower electricity prices in the 2010s worried many nuclear plant operators. While the cost of constructing new nuclear power plants had always been high, operational costs had typically been lower than those of fossil-fired stations. However, the increased availability of natural gas, coal, and renewables changed the picture. Prices dropped to a point where even debt-free nuclear power plants could no longer take their profitability for granted. Rising maintenance costs for the world's aging reactor fleet exacerbated the trend. This problem became more pressing in light of regulatory requirements developed in response to 9/11 and the Fukushima disaster. Many nuclear power plants faced a difficult choice.

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New regulations forced them to invest in expensive new systems, but, given unpredictable electricity prices, they could not be sure whether the plant would earn a return on such investments. The alternative was to close their plant prematurely. Many of the Western world's operational plants were nearing the end of their lives, and some were plagued by frequent, often age-related, incidents and breakdowns. In this situation, one utility after another chose to shut down its reactors. It was simply too costly to stay in business.

In the United States, utilities operating single-reactor plants were the most vulnerable. In February 2013, for example, Duke Energy decided to close the Crystal River NPP in Florida. The single reactor at this site had been taken out of operation in 2009 for the replacement of its steam generators. During this process, the containment structure of the reactor was accidentally damaged. The utility then "evaluated the ability to successfully repair the unit, the risks associated with any repair and the repair scope as well as the likely costs and schedule." It was concluded that the repairs would be too costly, so the reactor was permanently closed. A similar decision was made for the Kewaunee NPP in Wisconsin, which went offline in May 2013. The owners cited "lack of economies of scale" as the main reason. They insisted that the closure decision was "the result of circumstances unique to the station" and that it did "not reflect the nuclear industry in general." Yet it was followed by multiple similar closures elsewhere in the United States. In California, the San Onofre Nuclear Generating Station (SONGS) had invested in new steam generators in 2009 and 2010 and applied for a twenty-year lifetime extension for its two remaining reactors on that basis. However, in early 2012, the new steam generators were found to be leaking, necessitating costly repairs and an extended regulatory review process. In June 2013, Southern California Edison (SCE) decided to permanently shut down both units due to perceived uncertainties about the regulatory process and because "it is uneconomic for SCE and its customers to bear the long-term repair costs for returning SONGS to full power operation."[34]

In 2014, Entergy, another US utility, retired its single-reactor Vermont Yankee NPP. This plant had been awarded a twenty-year license extension in 2011 following a heated struggle between pro- and antinuclear stakeholders. That conflict became irrelevant when Entergy decided to close the plant anyway, citing the shale gas revolution, "the financial impact of

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cumulative regulation," and "wholesale market design flaws." In May 2016, Omaha Public Power District (OPPD), in a similar move, decided to shut down the Fort Calhoun NPP's single reactor, citing "market conditions, including historically low natural gas prices and lower energy consumption." Next, the historic Oyster Creek NPP—the erstwhile "loss leader" that had paved the way for nuclear power's commercial breakthrough in the mid-1960s—closed in 2018. Although the plant had received a twenty-year license extension in 2009, the utility responsible, Exelon, decided in 2010 to retire the plant early "after revisions to New Jersey's water use rules would have required it to build new cooling towers at an estimated cost of more than USD800 million." This was followed in 2019 by the closure of the Pilgrim NPP, which was interpreted as "the result of a number of financial factors, including low wholesale energy prices," and the retirement of the remaining reactor at Three Mile Island. The Duane Arnold and Indian Point NPPs followed suit in 2020 and 2021, respectively, and the Palisades NPP closed in 2022. The shutdown trend only came to an end after Washington intervened by passing the Inflation Reduction Act (IRA) in August 2022, which provided strong financial incentives to keep reactors in operation.[35]

The situation was similar in Europe, particularly in countries with liberalized electricity markets. Sweden was a case in point. There were no large-scale antinuclear demonstrations in Sweden after the Fukushima disaster, and the government had no intention of enforcing reactor shutdowns. During much of the 2010s, however, there was a marked downward trend in Swedish electricity prices, linked to the availability of cheap fossil fuels in continental Europe and rapid growth of domestic wind energy investment. This made the economics of continued reactor operation uncertain. Moreover, following the Fukushima disaster, the Swedish Radiation Safety Authority (SSM) issued an order requiring expensive "independent core cooling systems" (ICCS) to be installed at every nuclear power plant in Sweden by 2020. The government also increased a special tax that had been levied on the country's nuclear power plants since 2000, from 12,648 to 14,770 Swedish kronor/MW of installed capacity. These trends combined to render nuclear power unprofitable, prompting the relevant utilities to close four of the country's ten operational reactors. Two units at Oskarshamn were retired in 2016 and 2017, followed by two more at Ringhals in 2019 and 2020. However, when a new government took office in 2022, it set out to halt this

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trend by offering generous financial support to the nuclear industry, hoping to stop further shutdowns and stimulate new reactor projects.[36]

Unsurprisingly, numerous nuclear reactors were also closed in Japan during the 2010s. In the immediate aftermath of the Fukushima disaster, a lengthy study was initiated to reevaluate the nuclear safety of all plants, and in the meantime, all reactors were taken out of operation. In 2013, Japan's Nuclear Regulation Authority (NRA) published new regulatory requirements. Based on these, utilities were invited to apply for permission to implement overhaul programs involving extensive backfits of existing reactors. Each reactor was required to install a "specialized safety facility" (SSF) by 2023 at the latest. However, many reactors were so old that investing in such systems did not seem financially justifiable. Instead, they were permanently retired. In 2015, Kansai Electric Power announced that the troubled first two reactors at the Mihama NPP (cf. chapter 5) would be closed, while Japan Atomic Power opted to decommission its pioneering Tsuruga-1 reactor. Chugoku Electric Power decided to permanently close the Shimane-1 unit. Kyushu Electric Power did the same for its Genkai-1 station. A year later, Shikoku retired Ikata-1 "due to the estimated JPY 170 billion cost of upgrades required." This was followed by the decision to close Ikata-2 and Onagawa-1 in 2018.[37] In this way, eight Japanese reactors were permanently closed in the course of only a few years. Importantly, this happened despite a pronuclear government policy that defined nuclear power as indispensable to Japan's energy supply, even after the Fukushima disaster. Further closures followed over the next few years, bringing the total number of reactors that were closed in the post-Fukushima period to twenty-two (while another five reactors had been closed before the accident).[38]

Envirotechnical Dilemmas as Obstacles to China's and India's Nuclear Expansion

The dynamics of nuclear energy in "emerging economies" such as China and India differed from those in Japan and the Western world. Struggling to meet rapidly increasing electricity demand, these countries sought to utilize all possible energy sources to meet industrial and residential needs. Although nuclear power was rarely central to these efforts, the atom was regarded as a useful—and prestigious—addition to investments in coal- and

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gas-fired power plants and renewables. Virtually all emerging economies planned to use nuclear power to increase available production capacity. This resulted in a flurry of national plans and the initiation of a significant number of new reactor projects. At the same time, several older projects that had been abandoned in previous decades, such as Iran's Bushehr NPP and Brazil's Angra-3 reactor, were revived.

However, nuclear expansionism in the emerging economies was not without controversy. In China, there was growing opposition to nuclear power at local and regional levels, especially in the context of Beijing's ambition to build nuclear power plants in the country's interior. All of China's initial nuclear power stations were constructed along the coast, where the major industrial cities were located. However, the increasing demand for electricity in noncoastal regions made it natural to consider erecting nuclear power plants there as well. This geographical diversification posed a challenge in terms of cooling water supply, as the inland plants would have to draw their cooling water from rivers rather than the sea. Similar to the United States and Western Europe around 1970, this led to concerns about thermal and radioactive pollution of the country's waterways. There were also concerns about the negative effects of cooling towers, including plume shadowing, solar energy loss, and salt deposition, all of which were seen as "affecting the growth of local crops."[39]

Such fears were generally disregarded at the central government level, but they were taken seriously by county and municipal agencies. Concerns over drinking water supply had already been a major bone of contention in the case of China's first nuclear power plant. As a result, it was built not on the Fuchun River as initially proposed but rather at Qinshan, a coastal site in Zhejiang. Beginning in 2005, the government attempted to promote riverine nuclear power plants again, starting with a proposed station in the upper reaches of the Han River in the northeastern part of Guangdong Province. Similar to the situation with the Fuchun River, this proposal sparked concerns in the lower reaches of the Han River, raising fears that the nuclear project would endanger drinking water safety and destroy the river ecosystem through thermal pollution. People's deputies from nearby cities raised the issue at the provincial People's Congress. The provincial government and the China Guangdong Nuclear Power Group (CGNPG) did their best to reassure the deputies that the nuclear power plant would be safe and have minimal environmental impact, but the protests continued. Eager not to

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alienate the local population, the provincial government eventually backed down from the project. They declared that the proposed station would be postponed and that further nuclear power projects in Guangdong would be "restricted to the coastline until 2015."[40]

After the Fukushima disaster, the opposition to inland nuclear power plants in China intensified. A striking case was the protest against the proposed Pengze NPP, which was planned for construction on the Yangtze River where this mighty waterway formed the border between Jiangxi and Anhui provinces. The plant was to be built in Jiangxi, but stakeholders in Anhui, across the river, were extremely critical. In 2012, Wangjiang County, located in Anhui, began mobilizing against the nuclear project. A group of four retired county leaders led the protest movement. One of them was a former director of the regional water resources bureau, which lent the campaign considerable authority. The Yangtze River had been critical to the existence of Chinese civilization for thousands of years, and the specter of nuclear cooling threatening local agriculture and drinking water supplies caused dismay and perplexity among the local population. Numerous media outlets sent reporters to the region to cover Wangjiang's antinuclear movement during the second half of 2012.[41] Prominent members of the Chinese Academy of Sciences also supported the movement. In a policy petition to Premier Wen Jiabao, the scientists appealed for "high levels of caution when planning inland nuclear power projects." The combined efforts of the four seniors and the scientists were successful, as reflected in Beijing's decision in late 2012 to suspend not only the Pengze NPP but "all inland nuclear power projects during the 12th Five-Year Plan period (2011–2015)." When the thirteenth five-year plan of the power industry was released in November 2016, it still made no mention of any inland NPPs.[42]

In the 2020s, the Chinese government continued to push for nuclear construction, but the pace of expansion was more cautious than in the years before the Fukushima disaster. Inland nuclear power plants remained a contentious issue, and as of 2025, none had begun construction. As a result, the share of nuclear power in China's electricity mix stagnated at around 5 percent. As early as 2013, the share of wind energy overtook that of the atom, and by 2022, Chinese wind turbines generated nearly twice as much electricity as the country's nuclear power plants. In 2023, the share of solar energy, too, overtook that of nuclear power, while coal remained

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by far the most important electricity source, accounting for 62 percent of the total.[43]

India's efforts to increase its reliance on nuclear energy also faced obstacles. Beginning in 2007, the government earmarked a growing number of sites for nuclear construction. These plans sparked immediate local protest. An unprecedented surge in antinuclear activity followed, involving critical scientists, NGOs, and local populations across the country. One key dimension of the critique was the livelihood and cultural losses associated with land acquisition for nuclear projects.[44] Another issue, similar to concerns in China, was the intricate entanglement of inland nuclear power plants with rivers and riverine landscapes. In 2009, for instance, the government proposed building the Chutka NPP in the state of Madhya Pradesh. The plant was to consist of four 700 MW reactors that would draw cooling water from a reservoir in the Narmada River. This reservoir did not evoke positive memories in the region. Between 1974 and 1990, 162 villages had been submerged as a result of its construction, and their communities had been forcibly displaced. The nuclear project resulted in a second wave of displacement, as several villages that had been forced to relocate in the 1970s were evicted again. Moreover, the dammed river had come to play a key role in the agricultural and urban water supply through irrigation canals that served a vast region. Adivasi (indigenous Indian) communities living along its banks depended on the river for fishing. Fears of thermal and radioactive pollution, as well as the consequences of large-scale water withdrawals for nuclear cooling, sparked protests. Opposition to the project intensified after the Fukushima disaster, with fifty-four village councils joining forces in massive protests against the planned reactors. In response, the administrative authorities deployed "more than ten thousand police and paramilitary forces" to keep the local population at bay.[45]

Another controversial Indian project was the Gorakhpur NPP. Rather than building this inland nuclear station on a river, the government planned to construct it on the Bhakra Main Line, a major irrigation artery that supplied water for agricultural and domestic use to three Indian states: Punjab, Haryana, and Rajasthan. The canal was part of a larger hydraulic project centered on the massive Bhakra and Nangal dams, which were built on the Sutlej River—the easternmost tributary of the Indus—in the early days of independent India. In 2010, the Nuclear Power Corporation of India (NPCIL) selected the Gorakhpur site for the project, and in

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January 2014, Prime Minister Manmohan Singh laid the foundation stone for the station.[46]

The project sparked fierce opposition from farming communities. They objected to the government's attempts to forcibly acquire fertile farmland for the project and to the proposed diversion of water from the Bhakra Canal for nuclear cooling purposes. The station would use a recirculating cooling system with large cooling towers and remove around nine cubic meters of water per second from the canal. This would leave less water available for irrigation. Opponents noted that the plan contradicted the 1959 Bhakra water-sharing agreement between Punjab and Rajasthan, which specified that water from the canal would be used only for irrigation and hydropower generation. Opponents forcefully argued that diverting water for the nuclear station was "illegal and violative of the Right to Life under Article 21 of the Constitution." They also predicted that the continuous discharge of heated cooling water would lead to thermal pollution and possibly radioactive contamination of the canal. Moreover, they noted that the irrigation canal's embankments occasionally suffered breaches, causing disruptions in the water supply. How would the nuclear power plant handle such events?[47] The government and NPCIL continued to advance the project, but progress was slow. As of 2024, ten years after the groundbreaking ceremony, no construction had begun on the reactor buildings, and the government vaguely indicated that the first of four planned reactors might be operational by 2031.[48]

Of all new Indian nuclear power plants, the most controversial was the Kudankulam NPP in Tamil Nadu. It was a unique project in terms of both size and technology. The plan was to build as many as six Russian-designed VVER-1000 reactors on the shores of the Indian Ocean. The project originated from a Soviet-Indian agreement signed in the late 1980s. Planning resumed in the late 1990s, and construction of the first pair of reactors began in 2002. The endeavor was controversial from the outset. Fishing and farming communities were concerned about the plant's environmental impact. Among other things, the builders planned to divert freshwater from a reservoir built during colonial times on the nearby Kotai River. As in the cases of Chutka and Gorakhpur, this led to fears that the nuclear project would endanger the supply of drinking water and irrigation systems. Fishing communities along the coastline were concerned about radioactive discharges and thermal pollution of the coastal waters. They also anticipated that their access to the sea and traditional fishing grounds would be

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severely restricted due to security zoning. These concerns formed the basis of one of the most notable resistance movements in independent India. Largely women-led, the movement lasted for several decades under the banner of the People's Movement Against Nuclear Power (PMANP). Opposition escalated after the Fukushima disaster, by which time the first reactor was nearing completion. Prime Minister Singh alleged that the movement was being driven by "foreign NGOs and foreign money." This led to the criminalization and brutal suppression of the opponents. Meanwhile, the first two reactors at Kudankulam went online in 2013 and 2016. Construction began on two more units in 2017 and on another two in 2021.[49]

However, most nuclear power plant projects in India faced multiyear construction delays, and many planned projects failed to get off the ground. The delays were due not only to local opposition but also to cost escalations, technical failures, and most strikingly, legal obstacles in the form of the unusual Civil Liability for Nuclear Damage Act. Passed by both houses of Parliament in August 2010, this law allowed Indian nuclear operators to seek compensation from domestic and foreign manufacturers of reactors, turbines, pumps, and other items in the event of a nuclear disaster. Unsurprisingly, the equipment suppliers opposed the law, arguing that it "is contrary to international conventions and undermines the channeling principle fundamental to nuclear liability internationally." Nevertheless, the government was determined to ensure that any foreign supplier would pay for potential damage caused in India. In what followed, both foreign and domestic suppliers became reluctant to participate in Indian nuclear power plant projects.[50] This became a major factor contributing to the slowdown of nuclear expansion. In what followed, India shifted its focus to constructing fossil fuel power plants and investing in renewable energy. The share of nuclear power in India's electricity mix declined from 3.0 percent in 2011 to 2.5 percent in 2022. The atom's share was overtaken by that of wind energy in 2014 and by solar power in 2018. In the 2020s, solar and wind energy continued to expand rapidly in India, while nuclear power remained a marginal energy source.[51]

A Renaissance for the Nuclear Circular Economy?

Dilemmas related to the nuclear circular economy posed an additional challenge for countries pursuing nuclear expansion in the twenty-first century.

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In the Global South, securing fresh nuclear fuel was anything but straightforward. Governments, utilities, and nuclear agencies found that the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) architecture did little to facilitate access to foreign uranium and enrichment services. Against this backdrop, countries such as Brazil, Argentina, and Iran concluded that they needed to become independent of foreign suppliers by performing as many fuel-cycle activities internally as possible. However, just as in the 1970s, the prospect of the Global South mastering the full nuclear fuel cycle made the United States and other Western powers nervous. After all, enrichment and reprocessing technologies could be used for military purposes, and there was a sense that IAEA safeguards could not prevent a country from developing nuclear weapons if it desired to do so and possessed enrichment or reprocessing capability. Thus, the Global North did everything in their power to prevent the Global South from acquiring fuel cycle facilities. This hindered the development of nuclear power in many countries.

The only southern countries that successfully realized their civilian nuclear ambitions were those that sought cooperation with Russia and China. Russia had a long history of exporting nuclear technology, dating back to Soviet times. Its reactor sales to Finland and Central Europe, which began in the 1960s, were unique in that they always included full fuel services. Following Vladimir Putin's rise to power in 2000, Russia adopted an aggressive export strategy aimed at capturing a significant portion of the global reactor market. As before, the Kremlin offered all-inclusive packages. Rosatom agreed to supply enriched nuclear fuel and to take back the spent nuclear fuel if the recipient country so desired.[52]

China and India were the early targets of Russia's post-Soviet export drive. In 1999 and 2000, Russian and Chinese engineers began constructing two VVER-1000 reactors at Tianwan on the Chinese coast. Additional VVER units were erected at the same site and at Xudabu in the post-Fukushima period.[53] The other early Russian export project was India's Kudankulam NPP, mentioned above.

In 2017 and 2018, Rosatom continued its international expansion by selling two VVER-1200 reactors to Bangladesh, and between 2018 and 2022, the company began erecting four similar-sized reactors at Akkuyu in Turkey. Its engineers then started work on a similar multireactor complex at El Dabaa in Egypt. Apart from these new projects, Rosatom helped Iran revive its Bushehr project, where the Germans had begun erecting a massive

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nuclear power plant back in 1975 until the 1979 revolution disrupted all activities. The first Bushehr reactor went online in 2011, and construction of a second began in 2019.[54] In this way, Russia helped four newly industrializing countries—Bangladesh, Turkey, Egypt, and Iran—go nuclear by building their first commercial-scale nuclear power plants. Crucially, Russia guaranteed the supply of nuclear fuel for the lifetime of each reactor.

China, itself an importer of Russian reactors, sought to emulate Russia's export successes by offering generous nuclear deals to countries such as Pakistan and Argentina. In the case of Pakistan, whose nuclear program had suffered due to its refusal to sign the NPT and its 1998 nuclear-weapons test, China's CNNC delivered a 325 MW reactor for the inland Chashma NPP (erected on an artificial reservoir in the Indus River) in the 1990s. After 2005, the cooperation between the two countries was scaled up with the addition of three more 325 MW Chinese units at the same site. This was followed by two larger Chinese reactors at the Karachi NPP, where the historic KANUPP reactor had gone into operation in 1971. Crucially, these deals included a guaranteed supply of enriched nuclear fuel from China. Moreover, just like the Russians, the Chinese agreed to contribute to the financing of the Pakistani plants.[55] Thanks to these arrangements, Pakistan was able to bring no fewer than six electricity-generating reactors online by 2022. The share of nuclear energy in the country's official electricity mix grew to around 15 percent, the highest figure among all emerging economies.[56] In 2014–2015, Argentina negotiated a similar arrangement with CNNC for the construction of a Chinese reactor at the existing Atucha site, as well as a potential additional unit at a site yet to be determined. As in the Pakistani case, China guaranteed "the supply of enriched uranium and fuel assemblies throughout the life of the plants." At the time of writing, however, no Chinese reactor has actually begun construction on Argentine soil, and it remains to be seen whether Argentina can replicate Pakistan's success in leveraging nuclear cooperation with Beijing.[57]

In summary, the only viable way for the Global South to advance its nuclear programs and ensure a steady supply of nuclear fuel was to bypass the global market for uranium and enrichment services by cooperating with two authoritarian regimes that were willing to export both fuel and technology. By contrast, attempts to cooperate with democratic Western nations proved infeasible, as demonstrated most dramatically by India's failure to move forward with a multitude of proposed projects with reactor

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vendors such as Westinghouse, GE Hitachi, and Areva.[58] A remarkably successful project, however, was the completion of four Korean-made APR-1400 reactors at the United Arab Emirates' pioneering Barakah NPP.

Meanwhile, in the Western world, the main challenge concerning the nuclear circular economy was the back-end of the nuclear fuel cycle. In particular, nuclear waste management continued to be seen as the Achilles heel of nuclear power in Western Europe and North America. Finland and Sweden made the greatest technical and political progress. By the early 2020s, regulators and governments in both countries had approved their utilities' proposed solutions for the geological storage of spent nuclear fuel. This paved the way for the construction of repositories at Olkiluoto in Finland and Forsmark in Sweden.[59] Most other West European nations, however, along with the United States and Canada, were still far from making concrete decisions about how, where, and when to store their high-level nuclear waste. This perceived lack of progress contributed to nuclear skepticism in many countries.[60]

Reprocessing of spent nuclear fuel was another challenge that continued to plague the global nuclear industry. Britain's proposed THORP reprocessing plant was eventually approved for construction, but its completion was delayed over and over again. It was commissioned only in 1997, and it lived an unhappy life. The plant never operated as designed, there were numerous accidents and breakdowns, and in 2018 it was permanently closed. The old, troubled B205 reprocessing plant, for its part, ceased operation in 2022.[61] From then on it was no longer possible to reprocess spent nuclear fuel in Britain. The focus then shifted to the challenge of what to do with the hundred tons of plutonium that the nation's reprocessing plants had generated over the years. Historically, the plutonium had been seen as a valuable resource, one that would be at the heart of the nuclear circular economy. In the twenty-first century, it was regarded as a nuisance. There were several proposals to recycle the plutonium by producing MOX fuel, but none were deemed profitable.[62]

Japan, disillusioned by repeated technical problems and excessive costs associated with the nuclear circular economy, also considered giving up reprocessing. A government study from 2004 found that, over the next sixty years, it would be significantly more expensive to reprocess the nation's spent nuclear fuel than to dispose of it directly. Another study, this time by the JAEC, arrived at similar results in November 2011. Despite these

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discouraging cost comparisons, Japan Nuclear Fuel Limited (JNFL) decided to push ahead with reprocessing, ostensibly for energy security reasons, as reprocessing would allow Japan to save on imported uranium. However, as in Britain, there were no plutonium-fueled fast breeder reactors on the horizon after the premature closure of the troubled Monju FBR. In that situation, the only way to put the recovered plutonium to productive use was to produce MOX fuel, which could be "burned" in those light-water reactors that were not permanently shut down after the Fukushima disaster. JNFL argued that using MOX fuel would allow the industry to "extract an extra 25–30% of energy from nuclear fuel." The other main advantage of reprocessing was the significant reduction in high-level waste volume. Yet, progress in building actual reprocessing capacity was slow. After Japan's pilot-scale reprocessing plant in Tokai closed in 2009, the country had no operational reprocessing facilities. The larger, commercial-scale Rokkasho reprocessing plant and its associated waste vitrification facility, which were under construction since the 1990s on the northern tip of Honshu Island, were plagued by technical problems. According to the original plans, the Rokkasho complex was to be commissioned in 2008, but as of 2025 it had not yet commenced operation.[63]

Russia was another country that struggled hard to close the nuclear fuel cycle, though with limited success. The historic RT-1 reprocessing plant at Mayak continued to reprocess spent VVER fuel, albeit at a slow pace. Construction of the larger RT-2 plant at Zheleznogorsk in Siberia was halted in 1989 due to antinuclear protests and a lack of funds. The project was revived in the early twenty-first century but faced many delays. As of 2025—four decades after the construction start—industrial-scale reprocessing at Zheleznogorsk had not yet begun. As a result, more and more spent fuel from Russian, Ukrainian, and Bulgarian VVER-1000 reactors piled up next to the RT-2 plant, being stored in pools. The arrival of more and more fuel elements eventually led to a spent fuel storage crisis, to which Rosatom responded by investing in a second, dry storage facility, the first stage of which was commissioned in 2012. This facility was also used to store RBMK fuel, which was not intended for reprocessing. In this way Zheleznogorsk became increasingly specialized in the interim storage of spent nuclear fuel rather than its reprocessing.[64]

In China, meanwhile, residents of Jiangmen in Guangdong Province took to the streets in July 2013 after learning that a brand-new nuclear

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fuel complex, consisting of a fuel fabrication facility, a conversion plant, and an enrichment plant, would be built nearby. After three days of demonstrations, during which the residents besieged the municipal government, officials opted to give up the project. Another Chinese street protest occurred in Lianyungang in Jiangsu Province, where CNNC planned to build a commercial-scale reprocessing plant in cooperation with France's Areva. The protests caused delays and stagnation in China's efforts to cope with spent nuclear fuel. As of 2025, no civilian reprocessing plant had gone operational in China, although a first pilot-scale facility was reported to be nearing completion. Whether China will be able to close the nuclear fuel cycle remains to be seen.[65]

Nature Strikes Back: Nuclear Energy in an Age of Climate Change

The vision of a nuclear renaissance was, as we have seen, closely associated with the perceived necessity of phasing out fossil fuels to prevent global warming. At the same time, the real-world effects of global warming, such as more frequent floods, droughts, and heat waves, posed new challenges to the nuclear industry. A 2021 study found that the number of weather- and environment-related outages at nuclear power plants worldwide had increased massively over the past few decades. In the 1990s, outages at nuclear plants due to environmental factors were rare. By the 2010s, the number of such events had increased by a factor of eight. In North America and East Asia, this was primarily due to more frequent storms, hurricanes, and typhoons. In Europe, the main dilemmas were water scarcity and high water temperatures in the continent's nuclearized river basins.[66]

Moreover, rising sea levels made coastal nuclear power plants more vulnerable to storms and floods. The fear of flooding, which increased after Fukushima, is clearly visible in the world's nuclearized landscapes. Many sites are surrounded by dikes, levees, and seawalls—or drainage canals, similar to the moats that once protected medieval castles. Currently, nuclear dike builders in Europe, Asia, and North America are extending and improving the dike infrastructure in hopes of reducing the risk of future tragedies. In Britain, a 2012 government report stated that twelve of its nineteen civil nuclear sites would be at risk of flooding by the 2080s. One of those twelve sites is Hinkley Point, where two new reactor blocks are currently under

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construction. Another dilemma is the accelerating erosion of the coastline, as exemplified by California's San Onofre NPP, which is no longer operational but still contains a large amount of nuclear waste stored in forty-five-ton sarcophagi on the beach.[67]

One of the most breathtaking "nuclear floods" occurred during an Atlantic winter storm on December 27, 1999. At risk was the Blayais nuclear power plant in France, located in the Gironde estuary downstream from Bordeaux. The plant was surrounded by a system of earthen dikes, partly protected by rock piles, but the flood reached a staggering 5.3 meters above sea level, endangering this protective system. A breach in the dikes led to flooding of the site: "The waves moved the rocks protecting the dike, and part of it was washed away alongside the River Gironde." The flood destroyed electricity connections to the plant and stopped several safety systems from working, including "the two low-head safety injection pumps and the containment spray pumps. The pumps were deemed by the operator to be totally unavailable." Most critically, one of the two pumps that supplied seawater to the cooling system failed at the same time that the flood knocked out the emergency cooling system.[68] Nature's agency and the messy hybridization of old and new technologies—earthen dikes, electricity lines, protective rocks, safety injection pumps—jeopardized nuclear safety.

In the United States, flooding became especially problematic along the Mississippi, the Missouri, and their tributaries. In June and July of 2011, the Missouri River rose so high that the Cooper NPP in Nebraska was forced to enter lengthy emergency status. Measures taken to cope with the crisis included the "strategic placement of sandbags at building entrances and important facilities." The Fort Calhoun plant, located 150 kilometers upstream from Omaha, suffered worse consequences. It was completely surrounded by the floodwaters. Its flood protection measures were basic and relied on a temporary levee in the form of "an 8 feet (2.4 m) high and 2,000 feet (610 m) long rubber berm" surrounding the reactor building. However, the berm collapsed after a few days, allowing water to enter some of the buildings. Fortunately, the plant had been shut down two months earlier for refueling, so there was no risk of a core meltdown caused by the flood. Still, operators were concerned about decay heat from a pool containing spent nuclear fuel. Three years later a similar event occurred at the St. Lucie nuclear station in Florida when heavy rainfall "flooded the Unit 1 reactor auxiliary building with 50,000 gallons through flood barriers that had been

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missing since at least 1982."[69] Such events are likely to become more common in coming decades.

More frequent heat waves and droughts pose a different set of problems. In Europe, 2003 was a turning point in this regard, ushering in a new era of dry nuclear summers. That year, Spain's nuclear regulators ordered the shutdown of the country's reactors due to excessive heat and low water levels. French, German, and Romanian authorities did the same for some of their plants, while other facilities were granted unique permits to exceed their normal thermal discharge limits and were allowed to continue operating. Electricity shortages were unavoidable. In response, the French state-owned utility EDF cut nuclear electricity exports to Italy, resulting in blackouts in many Italian cities. Then, in 2006, a dry summer in the United States forced several nuclear power plants to reduce output to avoid illegally overheating the nation's waterways. In August 2008, the Tennessee Valley Authority (TVA) lost one-third of its total nuclear electricity production for the same reason. The TVA faced similar situations in 2010 and 2011. In Europe, the exceptionally hot, dry summers of 2018, 2019, 2022, and 2025 were extremely challenging for nuclear operators. In some locations, even the sea became too warm for cooling, forcing the closure of coastal nuclear plants. Climate change is also a concern for many countries in the Global South that are developing nuclear power. As we have seen, many of the planned reactors in India are located inland in areas with sensitive hydrology. As water becomes scarcer there, nuclear power plants will have to compete with agriculture and drinking water supplies for available resources.[70]

Nuclear Energy Is Dead—Long Live Small Modular Reactors?

Beginning in 2020, the nuclear debate shifted in an interesting way. "Small modular reactors" (SMRs) became the new buzzword, heralding a new vision for nuclear energy's global future. Since the heyday of the 1960s and 1970s, nuclear engineering had focused on large and increasingly complex nuclear steam engines. The concept of SMRs reflected the industry's acknowledgment that this approach had reached a point that increasingly looked like a dead end. SMRs embodied the dream that the nuclear industry could reinvent itself radically. By doing so, the enthusiasts argued, the industry could come to grips with the clashes and contradictions resulting from the historical attempts, examined in this book, to marry nuclear

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science with steam engineering, hydraulic engineering, and circular economy practices.

At the micro level, the transition to SMRs was seen as an elegant solution to the classic safety problems associated with large nuclear power plants. For instance, the smaller size meant there was less decay heat to remove during an emergency shutdown, which made a core meltdown less likely. Similarly, natural circulation was considered sufficient to cool a small reactor core, reducing SMRs' dependence on active machinery and vulnerability to external electricity blackouts. Furthermore, many SMRs were designed with the reactor core, steam generator, and pressurizer inside a single pressure vessel. This eliminated the need for large external pipes that could rupture, thereby reducing the potential for loss-of-coolant accidents. At the meso level, SMRs' envirotechnical entanglements did not involve the same levels of thermal pollution, dependency on cooling water, or landscape reengineering that had always accompanied large nuclear power plants. And finally, at the macro level, advanced SMRs promised better spent fuel solutions and less radioactive waste.

A flurry of SMR types were discussed, and by 2024, more than one hundred proposed designs were participating in the race to commercialization worldwide.[71] Many of these were closely linked to the "new" and "advanced" nuclear technologies that fell under the Generation IV umbrella, discussed earlier in this chapter. This reflected an ultimate SMR vision in which the reactors were not only small and modular but fundamentally different from traditional light-water reactors in a technological sense. Some were "fast" rather than "thermal" reactors, and many models relied on coolants other than water, such as lead or sodium. The problem was, as the engineers acknowledged, that such reactors needed "a great deal of research and development to be sufficiently reliable and economic to justify their commercial large-scale deployment."[72] Just like in the 1950s and 1960s, when the first civilian nuclear reactors were developed, the technological challenges for SMRs proved to be greater than expected. By the early 2020s the envisaged commercial deployment of Generation IV had been "postponed to around 2045 as technological challenges are high for these new types of reactors."[73]

Another dilemma for SMRs was precisely their small size. Historically, nuclear engineers had sought to make their reactors competitive with fossil-fueled power plants by making them larger. For decades, this had

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been regarded as the only way to make nuclear power commercially viable. SMR promoters hoped to overcome the economic disadvantages of small reactors by manufacturing large quantities of identical units in factories, rather than building unique ones on site. This meant that the success of SMRs hinged on the creation of a mass market. Before such a market emerged, there could be no profitability. Moreover, considerable uncertainty remained about the actual cost of building, operating, maintaining, and decommissioning a small reactor. A 2024 survey found that "overnight capital cost" estimates for SMRs ranged from 3,160 €/kW to 20,153 €/kW. While a few optimistic estimates suggested that SMRs would be cheaper than large traditional reactors, most pointed to higher costs for SMRs compared to large reactors.[74] This made many potential investors skeptical, especially at a time when they could easily invest in booming wind and solar energy projects instead. In the end, most SMR designs could only be pursued with the help of generous public subsidies. These subsidies helped launch SMR projects in the United States, Russia, China, Japan, Canada, South Korea, Britain, and other countries.

In fact, the most promising SMR projects were not Generation IV reactors but rather scaled-down versions of existing light-water reactors. For instance, GE Hitachi Nuclear Energy, formed from the 2007 merger of General Electric and Hitachi, reduced the size of their traditional boiling water reactors from around 1,000 MW to 300 MW and introduced the BWRX-300 model. They marketed this machine by arguing that the reactor used "a licensed and proven fuel design and the incorporation of proven components and supply chain expertise" and claiming that, despite this historical path dependence, it featured "dramatic and innovative design simplification."[75]

Another SMR promoter was NuScale, a startup company that partnered with a coalition of Utah municipal utilities and the historic Idaho National Laboratory to develop a scaled-down version of the pressurized water reactor with federal funding. The company launched an ambitious project to build six 77 MW reactors of this type at the Idaho site by 2030. In January 2023, however, NuScale reported that the target price for power from the plant had "jumped 53%," raising concerns about the project's economic viability. In November 2023, NuScale opted to abandon the project. Analysts interpreted this disappointing decision as "a blow to U.S. ambitions for a wave of new nuclear energy to help fight climate change."[76]

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Conclusion

Expectations of a "renaissance" for nuclear power were based on three main ideas. First, nuclear power was rebranded as a sustainable, low-carbon energy source in an age of climate change. Second, nuclear power was framed as an alternative to unreliable and increasingly expensive fossil fuels. Third, there was a strong belief in the nuclear industry's ability to reinvent itself by developing SMRs, disaster-free reactors, and proliferation-resistant fuel technologies. Based on these expectations, enthusiasm for nuclear power increased markedly worldwide after the turn of the millennium.

However, it proved more difficult than expected to escape the historical legacies of nuclear power as a hybrid technology, born from a military-oriented nuclear science and its merger with traditional steam engineering, hydraulic engineering practices, and circular economy ideals. At the micro level, the nuclear industry struggled to overcome the cost-complexity trap, which made nuclear power plants arguably safer but also more expensive over the years. The 2011 Fukushima disaster exacerbated this trend. There was also a mismatch between the hopes for a nuclear renaissance and the simultaneous quest for liberalized electricity markets. The combination of exceedingly expensive reactors, a free market, and unpredictable electricity prices made it difficult for utilities to commit to new nuclear plants without substantial government guarantees and subsidies. Hence, almost all new nuclear projects were launched in countries with regulated rather than liberalized electricity markets, predominantly in nations with authoritarian governments and limited political freedom.

Newly industrializing countries, such as China and India, invested in all available electricity-generating technologies, including nuclear energy. However, concerns over wet nuclear extractivism and fears of accidents sparked antinuclear protests, which slowed down nuclear expansion. As a result, renewables, which were perceived as far less complicated, gradually overtook nuclear energy in these nations' electricity mixes. Another issue was the growing number of unplanned outages at major nuclear power plants around the world due to droughts, heat waves, floods, and storms. Ironically, the very climate change that increased interest in nuclear power as a low-carbon energy source created new environmental vulnerabilities for the nuclear industry.

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Meanwhile, at the macro level, the supply of nuclear fuel and the management of spent fuel and nuclear waste remained problematic. Building on its tradition of selling reactors to Eastern European countries alongside full fuel cycle services, Russia seized the opportunity in the global reactor market by offering "package deals" to countries interested in building new nuclear plants, primarily in the Global South. China aspired to a similar role, although as of the mid-2020s, its only achievement in reactor exports was to Pakistan. The Western world was marginalized in both reactor sales and the fuel business. Overall, however, Russian and Chinese efforts to promote nuclear power worldwide were insufficient to result in more than marginal additions to the global reactor fleet. Consequently, by the early 2020s, nuclear power's share of the global electricity mix had been cut in half from its 1996 peak.

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7 Epilogue: The Global Atom Between Past and Future

Atomic Disenchantment and Nuclear Cognitive Dissonance

In an era marked by climate change, political populism, geopolitical turmoil, and technological disruption, the future of nuclear power remains as contentious as ever. The debate about the atom in the 2020s is both heated and ambiguous. On the one hand, we hear that nuclear power is seeing a revival, that numerous new reactors will soon be built worldwide, and that new, more advanced atom-splitting technologies are being worked out by creative teams of scientists and engineers. Powerful actors, from the White House to the International Energy Agency (IEA), view nuclear power as a vital component of solving various problems. Without the atom, the enthusiasts tell us, complete decarbonization will never be possible—especially in an age of artificial intelligence with its enormous electricity needs. Additionally, avoiding nuclear energy would increase our dependence on unreliable dictatorships for fossil fuel supplies. Alternatively, our electricity grids would suffer repeated breakdowns as they are overwhelmed by intermittent renewables. Many governments, including those of France, Britain, China, and India, are firmly committed to nuclear investment, regardless of the cost. The message is clear: Nuclear power's role will grow more prominent in the coming decades.

On the other hand, the real-world trend, in terms of nuclear power's contribution to the global electricity mix, is a gradual and seemingly unstoppable decline. The downward trend has been more pronounced in some parts of the world than in others. In Europe, where about a third of the world's nuclear power plants were built, there were 178 reactors in operation in 1989. Since then, the number has dropped by 38 percent

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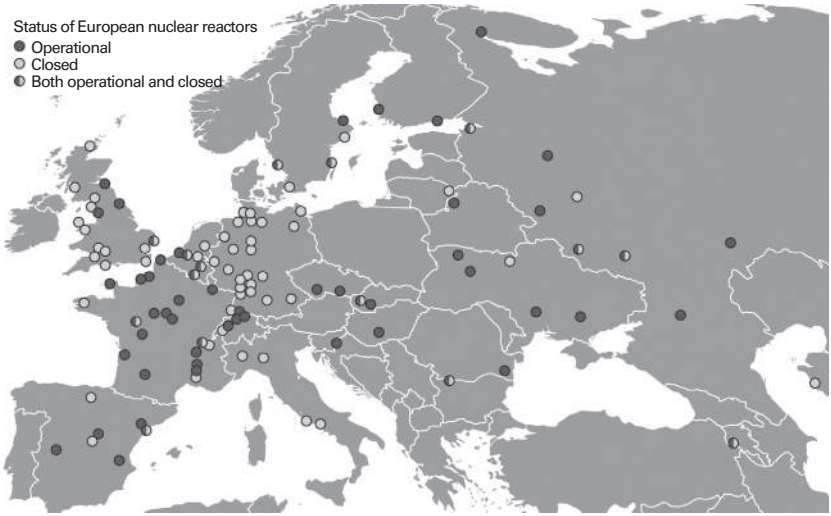

Figure 7.1
Map showing the locations of Europe's operational and decommissioned nuclear power plants. Since the 1990s, more than a third of all European nuclear reactors used for electricity generation have been permanently shut down. *Source*: Author's own work/Red Geographics.

(figure 7.1). Curiously, even in strongly pronuclear European countries, reactors are being closed and nuclear power's role is shrinking. Sweden has closed six of its twelve commercial reactors, and the United Kingdom, which once operated forty-five reactors, now has only nine. The United States aimed to build a thousand nuclear steam engines in the 1970s. About one hundred reactors were in operation by the late 1980s. Since then, only two additional reactors have become operational, while twenty-six have been permanently shut down.[1]

In Japan, all large-scale reactors were closed following the 2011 Fukushima disaster. Some have since been permitted to resume producing electricity, while others have been permanently retired, and no new reactors have been built. Taiwan shut down four of its six reactors. Many countries in the Global South continue to dream about the atom, but the actual outcome has been disappointing. Only a few southern countries have managed to start up one or more commercial reactors. Everywhere else in the Global South, nuclear power accounts for zero percent of the electricity mix. China is the country that has brought the most new reactors online in

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the twenty-first century. Despite Beijing's firm commitment over the past two decades, however, nuclear power's share of the country's electricity mix has declined in recent years, reaching 4.4 percent in 2024. As discussed in the previous chapter, nuclear power has been surpassed by wind and solar energy. A similar situation exists in India, where nuclear power contributes a meager 2.7 percent to electricity generation.[2]

There is thus a remarkable discrepancy between what many analysts and stakeholders think will happen in the future and what is currently happening in the world, between material trends and the promises of the future. Whether the global nuclear industry can be revived remains to be seen. Currently, it is in a phase of decline rather than growth. This is despite a number of very attractive features of nuclear fission, such as the immense energy density of uranium, the lack of carbon, sulfur, and nitrogen emissions, and the high degree of technological sophistication. In the early days of nuclear power, it was more or less taken for granted that, given these advantages, the atom would soon replace fossil fuels and older energy sources. The future, many observers believed, belonged to the atom. We are now back there, in an age of expectations.

The Future of Nuclear Power

In order to understand the prospects of nuclear power overcoming the past half century of stagnation and decline, it is crucial to understand the history of atomic disenchantment. In particular, we must ask ourselves: Why did nuclear power, despite its many attractive qualities, fail to become a dominant energy source?

This book has sought to answer this question by examining the interaction between nuclear science and a set of older technologies and practices. Over the years, the encounter between the new and the old generated challenges on three different scales. At the micro level, scientists and engineers struggled to integrate their bomb-making experiences from the military with the tradition of steam engineering, a field rooted in the Industrial Revolution and the development of technology for burning fossil fuels. At the meso level, efforts were made to integrate nuclear power plants into the surrounding landscape, particularly ensuring the supply of cooling water through traditional hydraulic engineering practices with deep historical roots. At the macro level, there was a need to develop effective nuclear

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fuel cycles inspired by the age-old ideal of recycling resources. The Faustian nature of nuclear engineering, in terms of its violent, military origins and the extraordinary health and environmental dangers associated with radioactivity, ensured that these efforts to merge the new with the old were fraught with tension on all three levels. In most cases, these tensions proved difficult to resolve in socially, politically, and economically acceptable ways. This paved the way for atomic disenchantment nearly everywhere in the world.

So, what can we expect in the future? Is the decline of nuclear power definitive, or might the long-awaited "nuclear renaissance" finally materialize? Will we see a new, dynamic phase in the history of global nuclear energy and a new boom in nuclear investment?

In 2025, the IEA published an enthusiastic report claiming that "interest in nuclear energy today is at its highest levels since the oil crises of the 1970s, with support for expanding the use of nuclear power now in place in more than 40 countries."[3] The agency noted that global investment in nuclear power had grown rapidly from $41 billion in 2019 to $67 billion in 2023. Of this total, $25 billion was allocated for extending the operational lifespan of existing reactors, while $42 billion went to new projects.[4] This may sound like a lot of money. And yet, these figures pale in comparison to the massive global investment in solar photovoltaic (PV) technology, which reached $480 billion in 2023, twelve times more than new nuclear power projects, as the IEA observed in a separate report. Total investment in renewable power reached $735 billion, while $1,090 billion was spent on fossil fuel generation technologies. Overall, nuclear power accounted for only 3.5 percent of global investment in electricity generation, including both new reactor projects and life extensions.[5] These investments came predominantly from government sources, while private spending on nuclear power remained extremely limited.

In the face of such figures, it would be odd to suggest anything other than that nuclear power will remain, at best, a marginal source of energy on a global scale. Once hailed as a revolutionary technology that would transform the world's energy supply forever, as a game changer in global energy development, as a source of power "too cheap to meter," and as a technology that no country could do without, nuclear energy has become increasingly supplementary and optional. Investment in nuclear power has not died out, nor has public and political enthusiasm for the atom.

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But what the nuclear industry is fighting for today is not, as in the 1960s and 1970s, global dominance. It is struggling to maintain a niche role in a global energy system dominated by fossil fuels and renewables, as well as its role as an important contributor to electricity generation in a few specific national settings. It is a struggle for survival.

So why are governments and private industry not investing more in nuclear energy? Why are renewable energy sources so much more popular? And why do investments in fossil fuel continue to outpace nuclear investments? To understand this, we must once again return to nuclear science's three unhappy marriages. At the micro level, nuclear technologies, born out of the historical hybridization of military nuclear endeavors and steam engineering, continue to grow ever more complex and expensive. At the meso level, nuclear power's merger with traditional hydraulic engineering practices continues to raise local and regional concerns, as evidenced by recent developments in Asia and elsewhere and exacerbated by the impact of climate change on wet nuclear extractivism. And at the macro level, the dilemmas related to uranium mining, enrichment, spent fuel management, and nuclear waste disposal serve to dampen the enthusiasm for commercial investment in nuclear power in many countries.

Small modular reactors (SMRs) can be understood as a response to these various dilemmas, the idea being that combining smaller-scale and more advanced technologies will make it possible to overcome the persistent obstacles at the three spatial levels. The SMR development is intriguing, and the dynamics of innovation in the industry are fascinating to follow. However, it remains to be seen whether and when SMRs will be able to reinvigorate the global nuclear industry. While it seems doubtful that North America or Europe will be able to generate the necessary mass market to make SMRs commercially attractive, it will be interesting to observe SMR investments in China, where a large market is more likely. Will China be able to replicate its spectacular success with wind turbines, solar cells, and electric vehicles? Can Chinese companies, backed by an authoritarian government's generous support, drive down the price of SMRs enough to make them irresistible elsewhere in the world? And if so, will European and North American utilities and regulatory agencies be willing to trust the safety of Chinese-built SMRs? If yes, SMRs may have a commercial future within the niche role that nuclear power may still play in the global energy system.

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It is safe to say, however, that SMR proponents, like nuclear visionaries of past, will face challenges on the three scales that have been the focus of this book. At the micro level, concerns are likely to arise over the safety of SMRs as scaled-down versions of conventional nuclear steam engines. At the meso level, we are likely to see debates about the envirotechnical entanglements of SMRs. And at the macro level, there will certainly be obstacles along the way as far as SMR fuel cycles are concerned. Overall, SMRs, the latest version of the nuclear steam engine, will have to go through trial-and-error processes similar to those of large-scale plants in the 1950s and 1960s. These processes will inevitably involve disappointments, failures, and accidents.

A more pressing question, especially in North America, Europe, and Japan, is whether the nuclear industry can replace aging nuclear power plants with new ones. Many old nuclear power plants are currently licensed to operate until the 2040s. However, sooner or later, they will need to be retired. Since constructing new large reactors can take ten, fifteen, or even twenty years, decisions regarding the construction of replacement reactors must be made sooner rather than later. France, for example, will retire its fifty-six old reactors over the next ten to twenty years. If EDF wants to maintain nuclear power's high share in France's electricity mix, it will need to build about forty new large reactors. Similarly, nuclear power in the United States will die a slow death in the coming years unless its ninety-four operating reactors are replaced by dozens of new ones. Russia is the only country that has begun to systematically replace its aging reactors with new ones.

The Next Disaster

History tells us that seemingly stable trends in nuclear policy can change quickly. Nuclear power has always been a vulnerable technology because it depends on ample government support. This support has been inconsistent and susceptible to internal and external events and trends. Sudden, unexpected changes in national nuclear policies following nuclear disasters are a case in point. Societies do not question the viability of air travel after a plane crash or call for the internet to be shut down after a cyberattack. By contrast, nuclear disasters have repeatedly led to calls to abandon the atom. This could happen again in the future, potentially disrupting global

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nuclear policies in unpredictable ways. In fact, history suggests that we may well see one or more nuclear disasters somewhere in the world in the coming decades. Although the nuclear industry has tried to convince regulators, governments, and the general public that their plants are completely safe—most recently in connection with the "stress tests" conducted after the Fukushima disaster—the probability of accidents can never be reduced to zero. It is impossible to know how probable a major disaster actually is. The historical record shows that the nuclear industry has repeatedly been surprised by events not considered possible when reactors were designed because they were deemed implausible. No one knows what the next "incredible" event will be or what its societal impact will be.

There are several reasons for concern. First, the world's nuclear reactor fleet is aging, making it more susceptible to failure. Additionally, most new nuclear power plants are being built in countries with high levels of corruption. How can regulatory agencies be guaranteed to be independent and trustworthy under such conditions? A third worrying aspect is the world's deteriorating geopolitical situation. Russia's invasion of Ukraine in spring 2022 highlighted the vulnerability of nuclear power plants to military aggression. The Zaporizhzhia Nuclear Power Plant, which has six large reactors, ended up on the front lines of the war. Since then, the situation at the site has been dire. In addition to being the target of military attacks, the plant's external electricity supply has been repeatedly cut off, endangering the cooling water pumps. Meanwhile, the Dnieper River, which served as the plant's ultimate heat sink, literally disappeared when the Kakhovka Dam, located farther downstream, was blown up in June 2023. Similarly, military conflicts and rising geopolitical tensions in the Middle East are worrisome in light of recent nuclear investment in countries such as Iran, the United Arab Emirates, and Egypt.

Overall, it is safe to say that the global history of nuclear energy is not over. And whatever awaits the disenchanted atom in the coming years and decades, its future will be anything but smooth and linear.

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Appendix: Nuclear-Energy Glossary

Uranium: A naturally occurring heavy metal. Natural uranium is mainly made up of the nonfissile isotope U-238. Only 0.7 percent consists of fissile U-235. However, U-238 can, in theory, be "bred" to fissile material by way of neutron absorption (see *fast breeder reactor*). Uranium is mined, milled into "yellowcake," and then processed/enriched as needed for different reactor types.

Plutonium: A radioactive element created inside reactors when U-238 absorbs neutrons; some isotopes (especially Pu-239) are fissile and can be used in reactors or weapons. Modes of reactor operation, fuel burn-up, and reprocessing determine whether the produced plutonium is "reactor-grade" or closer to "weapons-grade."

Nuclear fission: A nuclear reaction in which a heavy atomic nucleus (such as U-235 or Pu-239) splits into two or more lighter nuclei, releasing a large amount of energy and additional neutrons. This process is the fundamental source of energy both in electricity-generating nuclear reactors and in nuclear weapons.

Fission products: The lighter nuclei created when a heavy nucleus undergoes fission. These products are typically radioactive isotopes of elements such as iodine, cesium, strontium, and xenon, and they account for most of the radioactivity in spent nuclear fuel.

Decay heat: The heat produced by the radioactive decay of fission products after a nuclear reactor has been shut down. When the primary nuclear fission chain reaction is stopped, the "split" atoms remaining in the fuel rods continue to be highly unstable. As these isotopes decay into more stable forms, they release energy. Although this represents only a small fraction (initially about 7 percent) of a reactor's full thermal power, it is intense enough to melt the fuel in a large reactor if constant cooling is not maintained.

Military (plutonium-producing) reactor: A reactor configured and operated primarily to produce plutonium for weapons, rather than to generate electricity. Historically these reactors used graphite or heavy-water moderators in combination with natural uranium fuel.

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Thermal reactor: A reactor in which the chain reaction is sustained mainly by thermal (slow) neutrons—that is, neutrons that have been slowed by a moderator (usually water, heavy water, or graphite). Nearly all of the world's operational nuclear reactors are thermal reactors. They include all light-water reactors as well as gas-graphite reactors and heavy-water reactors.

Light-water reactor (LWR): A reactor that uses ordinary water (H_20) both as coolant and as moderator. Two dominant types of commercial LWRs were developed: pressurized water reactors (PWRs) and boiling water reactors (BWRs).

Pressurized water reactor (PWR): A light-water reactor in which water under high pressure cools the core and transports heat to a secondary loop (steam generator) where steam is produced for turbines; the primary loop remains liquid because of the high pressure.

Boiling water reactor (BWR): A light-water reactor in which water boils directly in the reactor vessel to produce steam that drives the turbine; control and safety arrangements differ from PWRs because steam and water come from the core itself. Most notably, BWRs lack steam generators.

Heavy-water reactor (HWR): A reactor that uses heavy water (D_2O, with the hydrogen nuclei having an extra neutron) as moderator. The advantage with this moderator is that heavy water absorbs fewer neutrons than ordinary water. This allows the reactor to run on natural (unenriched) uranium. Canada's CANDU reactor is the most well-known HWR design.

Gas-graphite (gas-cooled, graphite-moderated) reactor: A reactor family that uses graphite as a moderator to slow neutrons and a gas (usually carbon dioxide) as the coolant; British Magnox and AGR plants are classic examples.

Fast breeder reactor (FBR): A reactor that uses fast (unmoderated, high-energy) neutrons to sustain fission and is designed not only to produce power but also to "breed" more fissile material (in the form of Pu-239) than it consumes. This is possible through conversion of U-238 via neutron absorption. FBRs usually use liquid-metal coolants (e.g., sodium). Historically, it was expected that plutonium extracted through reprocessing of spent nuclear fuel would be recycled in fast breeders.

Megawatt (MW): A unit of power equal to one million watts. Nuclear and electrical engineers distinguish between megawatt-electrical (MWe) for electrical output and megawatt-thermal (MWt or MWth) for thermal heat from a reactor. Since the laws of thermodynamics stipulate that only around one-third of the heat generated in a reactor can be turned into electricity, the thermal energy generation is much higher than electrical output. A typical 1,000 MWe reactor, for example, produces around 3,000 MWth of heat.

Ultimate heat sink (UHS): The final destination for excess heat from a nuclear plant under both normal and emergency conditions—typically a large body of water such

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as a river, lake, or ocean. The UHS is critical for removing decay heat during shutdowns or accidents.

Cooling tower: A tall, often hyperbolic-shaped structure that cools the large volumes of water used to condense steam after it leaves the turbine. It transfers heat to the atmosphere via evaporation and convection. Cooling towers are typically used where natural water resources are insufficient or where thermal discharge limits force plant operators to install a recirculating cooling system.

Steam generator: A heat-exchange component in a pressurized water reactor. The high-pressure primary water from the reactor core flows through tubes inside the steam generator and transfers heat to the water circulating in a secondary cooling loop, producing steam that drives the turbine-generator.

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List of Abbreviations

AAR	Association of American Railroads (US)
ABWR	Advanced boiling water reactor
ACRS	Advisory Committee on Reactor Safeguards (US)
AEC	Atomic Energy Commission (US)
AECL	Atomic Energy of Canada Limited
AEOI	Atomic Energy Organization of Iran
AGNS	Allied General Nuclear Services (US)
AGR	Advanced gas-cooled reactor (UK)
AIF	Atomic Industrial Forum (US)
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (France)
ASME	American Society of Mechanical Engineers
BBC	Brown Boveri & Cie
BNFL	British Nuclear Fuels Ltd. (UK)
BORAX	Boiling reactor experiment series (US)
BWR	Boiling water reactor
CANDU	CANada Deuterium-Uranium reactor
CCNR	Canadian Coalition for Nuclear Responsibility
CEA	Commissariat à l'Énergie Atomique (France)
CEGB	Central Electricity Generating Board (England and Wales)
CGNPG	China Guangdong Nuclear Power Group
CNEN	Comitato Nazionale per l'Energia Nucleare (Italy)
CNNC	China National Nuclear Corporation
COGEMA	Compagnie Générale des Matières Nucléaires (France)
CRS	Compagnies Républicaines de Sécurité (France)
DAE	Department of Atomic Energy (India)
DPP	Democratic Progressive Party (Taiwan)
EBR	Experimental breeder reactor (US)
ECCS	Emergency core-cooling system
EDF	Électricité de France
EEC	European Economic Community (1957–1993; EU predecessor)
EIA	Environmental impact assessment

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ENEA	European Nuclear Energy Agency (1958–1972; renamed OECD NEA)
EPA	Environmental Protection Agency (US)
EPR	European pressurized reactor
ERG	Enrichment and Reprocessing Group (Japan)
EU	European Union
Euratom	European Atomic Energy Community
Eurochemic	European Company for the Chemical Processing of Irradiated Fuels
Eurodif	European Gaseous-Diffusion Uranium-Enrichment Consortium (France)
FBR	Fast breeder reactor
Framatome	Franco-Américaine de Constructions Atomiques (France)
FWS	Federal Wildlife Service (US)
GE	General Electric Company (US)
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
GW	Gigawatt
IAEA	International Atomic Energy Agency (UN)
ICCS	Independent core-cooling system
ICPR	International Commission for the Protection of the Rhine
IEA	International Energy Agency (OECD)
IPCC	Intergovernmental Panel on Climate Change (UN)
IRI	Istituto per la Ricostruzione Industriale (Italy)
JAEC	Japan Atomic Energy Commission
KANUPP	Karachi Nuclear Power Plant (Pakistan)
KBS	Kärnbränslesäkerhet (Sweden)
KEPCO	Kansai Electric Power Co. (Japan) *or* Korea Electric Power Corp.
KMT	Kuomintang (Nationalist Party of Taiwan)
KWU	Kraftwerk Union AG (Germany)
LNG	Liquefied natural gas
LWR	Light-water reactor
MOX	Mixed-oxide fuel (U–Pu)
MW	Megawatt
NEPA	National Environmental Policy Act (US)
NFS	Nuclear Fuel Services (US)
NOK	Nordostschweizerische Kraftwerke (Switzerland)
NPCIL	Nuclear Power Corporation of India Ltd.
NPP	Nuclear power plant
NPPD	Nuclear Power Plant Division (Canada)
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (US)
Nufcor	Nuclear Fuels Corporation of South Africa
NWK	Nordwestdeutsche Kraftwerke (West Germany)

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NZED	New Zealand Electricity Department
OECD	Organisation for Economic Co-operation and Development
OEEC	Organisation for European Economic Co-operation (1948–1961; OECD predecessor)
OPEC	Organization of the Petroleum Exporting Countries
OPPD	Omaha Public Power District (US)
PDRP	Power Demonstration Reactor Program (US)
PMANP	People's Movement Against Nuclear Power (India)
PNC	Power Reactor and Nuclear Fuel Development Corporation (Japan)
PUREX	Plutonium-uranium extraction (reprocessing method)
PWR	Pressurized water reactor
RAPS	Rajasthan Atomic Power Station (India)
RBMK	Reaktor Bolshoy Moshchnosti Kanalnyy (USSR, Chernobyl-type)
RWE	Rheinisch-Westfälisches Elektrizitätswerk (Germany)
SCE	Southern California Edison
SGHWR	Steam-generating heavy-water reactor (UK)
SMR	Small modular reactor
SNAP	Space Nuclear Applications Program (US)
Sredmash	Ministerstvo Srednego Mashinostroeniya (USSR Ministry of Medium Machine-Building)
SSEB	South of Scotland Electricity Board
SSF	Specialized safety facility (Japan)
STA	Science and Technology Agency (Japan)
TEPCO	Tokyo Electric Power Company (Japan)
THORP	Thermal oxide reprocessing plant (UK)
TVA	Tennessee Valley Authority (US)
TVO	Teollisuuden Voima Oy (Finland)
TÜV	Technischer Überwachungsverein (German Technical Inspection Association)
TWh	Terawatt-hour
UCOR	Uranium Enrichment Corporation (South Africa)
UHS	Ultimate heat sink
UKAEA	United Kingdom Atomic Energy Authority
Urenco	Uranium Enrichment Company (UK-Netherlands-Germany)
USSR	Union of Soviet Socialist Republics
VVER	Vodo-Vodyanoi Energeticheskii Reaktor (Soviet/Russian PWR)

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53. See "The Formation of the Consortia." This principle was intended to stimulate competition in the British nuclear industry. However, it soon became problematic, and the government later regarded it as one of the main reasons the United Kingdom failed to compete with the United States in export markets. See "Structure of the Nuclear Industry: Note of a Meeting in the Chairman's Office," October 15, 1964, UK National Archives, file AB 38/453.

54. Hill, *An Atomic Empire,* 237. Oldbury introduced a radical innovation: unlike earlier reactors, it did not have a steel pressure vessel; instead, it relied on prestressed concrete. The Wylfa project, for its part, marked the transition to a larger Magnox model with a capacity of 530 MWe—about twice that of earlier reactors. Cf. IAEA, *Nuclear Power Reactors*.

55. Atomic Energy Office, "Accident at Windscale No. 1 Pile on 10th October, 1957," UK National Archives, file AB 21/60. The nuclear experts argued that "the accident which happened at Windscale could not happen with the Calder Hall reactors or with the reactors being built for the Electricity Authorities," but design modifications nevertheless turned out to be necessary.

56. Thus, in 1962, for example, it was revealed that the Hunterston station, which in 1957 had been expected to cost £37 million, would ultimately cost £55 million, a 50% increase. See *Financial Times*, "What Has Gone Wrong with Nuclear Power?," March 16, 1962. Simon Taylor writes that "construction took 40% longer than planned, and the reported economic cost was artificially understated by not charging the research and development costs, by always assuming lower interest rates than actually applied." Taylor, *The Fall and Rise,* 15.

57. "Conclusions of a Meeting of the Cabinet Held at 10 Downing Street," June 23, 1959, UK National Archives UK National Archives, file CAB 128/33.

58. Hecht, *Radiance of France*, 64–78.

59. James Jasper, *Nuclear Politics: Energy and the State in the United States, Sweden, and France* (Princeton, NJ: Princeton University Press, 1990), 75.

60. Jasper, *Nuclear Politics*, 81–89; Hecht, *Radiance of France*, 87.

61. Hecht, *Radiance of France*, 99; "France's EDF-2 Is Already Well into the Installation Stage," *Nucleonics Week,* June 30, 1960.

62. Quoted in Jasper, *Nuclear Politics*, 76.

63. Radkau, *Aufstieg und Krise*, 37.

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64. Radkau, *Aufstieg und Krise*, 46–51, 108.

65. "Sicherheitsgutachten zur Inbetriebnahme," 1961, German Federal Archives, file B 138/4953; see also file B 102/41037. AEG, a large German company that had cooperated with General Electric in constructing fossil power plants for decades, built the Kahl plant.

66. Radkau, *Aufstieg und Krise*, 110–111.

67. Cf. Elisabetta Bini and Igor Londero (eds.), *Nuclear Italy: An International History of Italian Nuclear Policies during the Cold War* (Trieste: Edizioni Università di Trieste, 2017); Mar Rubio-Varas and Joseba De la Torre (eds.), *The Economic History of Nuclear Energy in Spain: Governance, Business and Finance* (Basingstoke, UK: Palgrave Macmillan, 2017).

68. Sigfrid Leijonhufvud, *Parentes? En historia om svensk kärnkraft* (Västerås, Sweden: ABB Atom, 1994); Olle Gimstedt, "Oskarshamnsverket I: En pionjärinsats i svensk kärnkraftutbyggnad," *Daedalus: Tekniska museets årsbok* 59 (1991): 244.

69. Michael Fischer, *Atomfieber: Eine Geschichte der Atomenergie in der Schweiz* (Baden, Switzerland: Hier und Jetzt, 2019), 115–133; J. M. Miller, "Incident at the Lucens Reactor," *Nuclear Safety* 16, no. 1 (1975): 76–79.

70. See, e.g., Karl-Erik Michelsen and Tuomo Särkikoski, *Suomalainen ydinvoimalaitos* (Helsinki: Edita, 2007); Henry Nielsen and Henrik Knudsen, "The Troublesome Life of Peaceful Atoms in Denmark," *History and Technology* 26, no. 2 (2010): 91–118; Tiago Santos Pereira et al., "Carnation Atoms? A History of Nuclear Energy in Portugal," *Minerva* 56 (2018), 505–528; Florian Bayer and Ulrike Felt, "Embracing the 'Atomic Future' in Post–World War II Austria," *Technology and Culture* 60, no. 1 (2019): 165–191.

71. Hurst, *Canada Enters the Nuclear Age*.

72. Robert Bothwell, *Nucleus: The History of Atomic Energy of Canada Limited* (Toronto: University of Toronto Press, 1988), 190–196, 225.

73. Bothwell, *Nucleus*, 253–295. Prior to that, the Canadians constructed a pilot-scale nuclear power plant in Rolphton, on the Ottawa River, that became operational in 1962.

74. Hamblin, *Wretched Atom*, 76–91; "Japan Began Foundation Work This Week for Its 166-MWe Calder-Type Reactor," *Nucleonics Week*, June 2, 1960.

75. Sarkar, *Ploughshares and Swords*, 81–85.

76. "Brazil Will Ask Bids in July for a 150-MWe Power Reactor," *Nucleonics Week*, May 5, 1960; Jennifer Eaglin, "The Water Origins of Brazil's Nuclear Energy Infrastructure," *Environment and History* 31, no. 1 (2025): 41–64. The estimated annual

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costs for a nuclear plant amounted to $417/kW, while the corresponding costs for new hydroelectric dams varied between $12.70 and $42.22/kW.

77. "South Africa Has Voted against Nuclear Energy," *Nucleonics Week*, January 11, 1962.

78. Hamblin, *Wretched Atom*, 18–21 (on Argentina) and 106 (on the Congo).

79. "The Need for Atomic Power Remains as Great as Ever," *Nucleonics Week*, May 26, 1960.

80. The cases of New York, Moscow, and Stockholm have already been mentioned. For the case of West Berlin, see Berliner Kraft- und Licht (Bewag)-Aktiengesellschaft, "Errichtung eines Kernkraftwerkes: Eine technische, wirtschaftliche und rechtliche Beschreibung" (Vertraulicher Bericht), May 18, 1962, German Federal Archives, file B 138/2265.

81. "Background Information on Atomic Power Development in the United States," in *Proceedings from the International Conference on the Peaceful Uses of Atomic Energy*, Geneva, Switzerland, August 8–20, 1955 (New York: United Nations, 1956), 725–726; "Alaskan Utilities Seriously Considering Small Nuclear Power Plant," *Nucleonics Week,* February 22, 1962.

82. Hanne E. F. Nielsen, "Remembering Antarctica's Nuclear Past with 'Nukey Poo,'" *The Conversation,* July 22, 2018; "PM-2A Goes Critical in Greenland," *Nucleonics Week*, October 6, 1960.

83. Hirsh, *Technology and Transformation*, 20, 37, 76.

84. Hirsh, *Technology and Transformation*, 43, 46, and 90.

85. E.g., "In Washington," *Nucleonics Week*, June 7, 1962; "Fate of the Small Pressurized Water Reactor Is In Question," *Nucleonics Week*, June 29, 1961; "AEC 'Defers Indefinitely' Process Heat Reactor and Small PWR," *Nucleonics Week*, November 30, 1961.

86. Quoted in Hirsh, *Technology and Transformation*, 68. For the Canadian case, see Bothwell, *Nucleus*, 286–287.

87. F. T. Binford, "Decay Heat Removal from Research Reactors," *Nuclear Safety* 1, no. 3 (1960): 34–35; Ford, *Cult of the Atom*, 66.

88. Ford, *Cult of the Atom*, 67; Thomas Wellock, *Safe Enough? A History of Nuclear Power and Accident Risk* (Berkeley: University of California Press, 2021).

89. Ford, *Cult of the Atom*, 51.

90. Wellock, *Safe Enough?*, 40.

91. Wellock, *Safe Enough?*, 15.

92. Wellock, *Safe Enough?*, 16.

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93. See, e.g., Hecht, *Radiance of France*; Radkau, *Aufstieg und Krise*; Leijonhufvud, *Parentes?*; On Switzerland, see Ernst Bachmann (chairman of the supervisory board, Nordostschweizerische Kraftwerke AG), "Begrüssungsworte," September 6, 1965. Aargau State Archive, file DB.K/0254/03.

94. Schmid, *Producing Power*, 116–117.

95. "Structure of the Nuclear Industry: Note of a Meeting in the Chairman's Office," October 15, 1964, UK National Archives, file AB 38/453.

96. Bothwell, *Nucleus*, 298–299.

97. This count is based on data in IAEA, *Nuclear Power Reactors*.

98. Quoted in Hill, *An Atomic Empire*, 178–179.

99. James Mahaffey, *Atomic Accidents: A History of Nuclear Meltdowns and Disasters, from the Ozark Mountains to Fukushima* (New York: Pegasus Books, 2014), xvii.

100. Radkau, *Aufstieg und Krise*, 109, 237, 240, 258, and 284.

101. See, e.g., "An AEC Study of Direct Conversion," *Nucleonics Week*, June 2, 1960; "Reports from Russia of a New Direct-Conversion Reactor Device," *Nucleonics Week*, December 7, 1961; "Martin Projecting Direct Conversion Reactors for Army Use," *Nucleonics Week*, October 25, 1962.

Chapter 2

1. Fifty cubic meters per second is often cited as the typical requirement of a 1,000 MWe reactor. However, volumes vary from plant to plant and depend on the technical design and factors such as the temperature of the external cooling source. Thus, e.g., the small (581 MWe) Ginna nuclear power plant in the United States required twenty-two cubic meters (six thousand gallons) of water per second, whereas two larger reactors at Calvert Cliffs required seventy-five cubic meters (twenty thousand gallons) per second each. See "New York Nuclear Profile 2010," EIA, https://www.eia.gov/nuclear/state/archive/2010/newyork/; Dan Tarlock, "The Story of Calvert Cliffs," in *Environmental Law Stories*, ed. Richard J. Lazarus and Oliver A. Houck, 1–40 (New York: Foundation, 2005), 17. Sweden's Barsebäck NPP was planned with four reactors totaling 3000 MWe, which together would require 150 cubic meters per second. Sydsvenska Värmekraftaktiebolaget, "Barsebäcksverket: Ansökan till Söderbygdens vattendomstol," Swedish National Archives.

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of Empire: Water, Aridity, and the Growth of the American West (New York: Pantheon Books, 1986); Julia Obertreis, *Imperial Desert Dreams: Cotton Growing and Irrigation in Central Asia, 1860–1991* (Göttingen: V&R Unipress, 2017); Francesca Bray, *The Rice Economies: Technology and Development in Asian Societies* (Berkeley: University of California Press, 1994). Irrigation resembles nuclear energy regarding the large-volume "water withdrawals" and the return of used water to a watercourse; see Diego Sesma-Martín, "Cooling Water: A Source of Conflict in Spain, 1970–1980," *Sustainability* 12 (2020): 4650. On early industrial water withdrawal, see Theodore Steinberg, *Nature Incorporated: Industrialization and the Waters of New England* (Cambridge, UK: Cambridge University Press, 1991).

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28. Gutting, "From Cooling Water War to Cooling Towers." For an overview of the European political debate on thermal pollution, see Jan-Henrik Meyer, "Thermal Pollution and the Origins of European Environmental Policy," in *The Nuclear-Water Nexus*, ed. Per Högselius and Siegfried Evens, 85–95 (Cambridge, MA: MIT Press, 2025).

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Chapter 3

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15. Hecht, *Being Nuclear*, 85.

16. Hecht, *Being Nuclear*, 97; Jacob Darwin Hamblin, *The Wretched Atom: America's Global Gamble with Peaceful Nuclear Technology* (Oxford: Oxford University Press, 2021). Hamblin notes that "Canada's response to the Indian nuclear test was to require that any country receiving its nuclear technology either sign the NPT or accept full-scope safeguards under the IAEA on all facilities. In addition, it demanded that Canadian supplies not be used for nuclear explosions, whether 'peaceful' or otherwise."

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25. "AEC Offers 25-Year Supply of Enriched Uranium Abroad, at US Prices," *Nucleonics Week*, December 7, 1961.

26. See, e.g., Hecht, *Being Nuclear*, 58.

27. R. Scott Kemp, "The End of Manhattan: How the Gas Centrifuge Changed the Quest for Nuclear Weapons," *Technology and Culture* 53, no. 2 (2012): 272–305; R. Scott Kemp, "Opening A Proliferation Pandora's Box: The Spread of the Soviet-Type Gas Centrifuge," *Nonproliferation Review* 24, no. 1–2 (2017): 113–115.

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34. Hecht, *Being Nuclear*, 96.

35. Kemp, "Opening a Proliferation Pandora's Box," 113–115.

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37. Joachim Radkau, *Nature and Power: A Global History of the Environment* (New York: Cambridge University Press, 2008), 12–15, 207–212.

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41. A. M. Allen (UKAEA) to H. Murrell (Council for the Protection of Rural England), July 16, 1974, UK National Archives, AB 45/242.

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canisters measuring 3.5 meters in height and 1.5 meters in diameter. Since the spent fuel emitted considerable decay heat, the canisters contained a system of cooling fins powered by electrical engines. As a disruption in the cooling could be disastrous, producing a core meltdown, the trains included a car loaded with emergency diesel generators. See Staatliche Zentrale für Strahlenschutz, "Konzeption zur Durchführung des Transports abgebrannter Kernbrennstoffkassetten des Kernkraftwerkes Rheinsberg" (undated), German Federal Archives, file DG 12/1021.

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82. Hamblin, *Poison in the Well*, 193, 252–253; Blowers et al., *International Politics of Nuclear Waste*, 49–50; Tatiana Kasperski and Anna Storm, "Eternal Care: Nuclear Waste as Toxic Legacy and Future Fantasy," *Geschichte und Gesellschaft* 46 (2020): 682–705. There were regional prohibitions on sea disposal in the Baltic (1974), the Mediterranean (1976), and the Black Sea (1992).

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89. Romy Dekker et al., "Long-Term Radioactive Waste Management in the Netherlands: Seeking Guidance for Decision-Making," in *The Future of Radioactive Waste Governance: Lessons from Europe*, ed. Maarten Arentsen and Rinie van Est (Wiesbaden, Germany: Springer, 2022), 29; on Italy, see Maria Rosaria Di Nucci and Andrea Prontera, "Nuclear Waste Governance in Italy: Between Participation Rhetoric and Regionalism," in *The Future of Radioactive Waste Governance: Lessons from Europe*, ed. Maarten Arentsen and Rinie van Est, 51–84 (Wiesbaden, Germany: Springer, 2022).

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92. Quoted in "U.K. Government Deciding Whether to Let BNFL Reprocess Foreign Fuel," *Nucleonics Week*, October 23, 1975; Blowers et al., *International Politics of Nuclear Waste,* 57–58.

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Chapter 4

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Chapter 5

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