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OCTOBER 2024

Reclaiming the Promise of Nuclear Power in India

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Introduction

Ever since its independence in 1947, India has obsessively pursued the goal of domesticating high technology. After the Second World War, atomic energy came to symbolize the acme of scientific prowess. It is therefore not surprising that a country whose nationalist narrative held that Western technological superiority had ensured its colonial subjugation would want to master the most important scientific advances as a means of preserving its newly secured freedom.

The history of atomic energy in India, however, predates the country's independence. Homi Bhabha, the visionary who founded India's nuclear program, created the Tata Institute of Fundamental Research (TIFR) in 1945 to pursue his myriad scientific interests, which included nurturing nuclear science to promote nuclear power production in India after it was freed from British rule.[1] Jawaharlal Nehru, India's first prime minister, knew Bhabha well and shared his belief that economic development required dramatically increased availability of electricity. Consistent with the common assumption then, that atomic energy would provide electricity plentifully and cheaply, Nehru created the Atomic Energy Commission (AEC) in 1948 to oversee India's efforts to develop nuclear technology and govern its accompanying institutions.[2] And in 1949, the Council of Scientific and Industrial Research—the agency overseeing science and technology development within India—would designate the TIFR as the nodal center for all large-scale projects in nuclear research.[3]

Because both Bhabha and Nehru understood that the atomic program had economic *and* strategic significance, the entire endeavor was placed—and still remains—under the direct personal authority of India's prime ministers. Along with the railways and the manufacturing of arms and ammunition, it was one of the three monopolies that was made exclusively the preserve of the Indian state.[4] It was immunized against all routine forms of government oversight and was generously funded on the expectation that nuclear energy would, in time, constitute a large share of India's electricity production.

India's nuclear establishment certainly made bold promises in this regard. In 1954, Bhabha declared that nuclear power would contribute 8,000 megawatts of electricity by 1980.[5] Today, some seventy years after Bhabha's announcement, India's current installed nuclear capacity stands at only 7,425 megawatts, with nuclear power accounting for a meager 3 percent of the country's total electricity production.[6] These hollow promises, however, were not simply remnants from an exuberant infancy. As recently as 2018, Dr. Jitendra Singh, who is currently the minister of state in the Prime Minister's Office and oversees the atomic energy program, informed the Lok Sabha (the Lower House of India's Parliament) that India's installed nuclear capacity would touch 13,480 megawatts (or 13.48 gigawatts electric capacity, GWe) by 2024.[7] In June 2024, however, this target was revised downward with the claim that the currently "installed capacity of 7.48 GWe will become 13.08 GWe by 2029."[8] Even more evidence along these lines can be adduced ad nauseum.

The Indian atomic energy establishment's long record of promising more than it could deliver has nourished the skepticism of numerous analysts who have looked closely at India's nuclear program. One scholar, M.V. Ramana, evocatively titling his analysis of its failures, *The Power of Promise*, detailed how despite significant budgetary allocations and strong political support from successive Indian leaders, India's atomic energy program has only proffered ambitious assurances but has not delivered on its undertaking to make nuclear power generation the solution to India's quest for energy independence.[9]

The usual defense against this charge of seriatim deceptions has been that India's 1974 nuclear test resulted in its power program being placed under Western sanctions for many decades.[10] The ensuing denial of access to technology imposed inordinate delays and cost overruns that prevented its nuclear power generation efforts from coming to fruition in the manner originally intended. Although there is much truth to this claim, it only undermines another cherished national belief that India's nuclear program, in contrast to Pakistan's, for example, "has always been self-reliant."[11]

On the contrary, India has relied on foreign assistance from the very beginning: from the very first reactor, Apsara, through the second reactor, CIRUS, to the current pressurized heavy water reactors (PHWRs) that form the mainstay of the Indian power program, external contributions were essential to the success of the Department of Atomic Energy's (DAE) endeavors.[12] This also includes foreign assistance in constructing the critically important reprocessing plant at Trombay, which would be used eventually to recover plutonium for New Delhi's nuclear weapons.[13]

The foreign contributions toward the maturation of India's nuclear program are thus all too real. Nor need India pretend otherwise because it does not take away from the DAE's myriad technological achievements, especially after 1974. That it has been able to build largely indigenous reactors since the Madras (1984–86) and Narora (1991–92) plants, redesign the calandria and end shield assemblies, piping, and cooling systems in later reactors, scale up the original 220-MWe (megawatts-electric) reactors to 540-MWe and eventually to 700-MWe designs, and design and build indigenous gas centrifuge plants for uranium enrichment, heavy water plants, and different kinds of reactor fuel pellets, all testify to the hard-won technological achievements of India's nuclear scientists and engineers over the years.[14] These successes cannot be overlooked despite the DAE's inability to make nuclear power the centerpiece of India's electricity generation efforts to date.

This failure resulted from a confluence of factors. Nuclear power plants have extraordinarily high upfront capital costs, a burden that is exacerbated in India by the exorbitant cost and complexities of land acquisition and, frequently, popular opposition to the construction of nuclear power plants on privately owned land.[15] Although most Indian administrations have generously funded the DAE's establishment expenses, they have been skittish about funding large-scale reactor construction because the cost of nuclear energy per unit has been higher than that associated with other energy sources such as renewables (even though it is unclear whether the implicit subsidies enjoyed by the latter are adequately factored into the comparison).

Consequently, the Nuclear Power Corporation of India Limited (NPCIL), the DAE's government-owned subsidiary that was formed in 1987 to oversee the construction and operation of nuclear reactors in India, invariably has to supplement the official resources available for reactor construction by relying on "internal and extra-budgetary resources" (IEBR), to include borrowing from commercial markets through the issuance of bonds.[16] Not surprisingly, then, the cost of interest payments often turns out to be greater than the cost of the project components themselves. And the latter, traditionally, has not been minimized either because the DAE/NPCIL's strategy of constructing new reactors either singly or occasionally in very small numbers (often through learning by doing and without conforming to a single standardized design) contributes to the increased cost of the power plants as the component suppliers cannot benefit from any economies of scale.

The problems frequently uncovered with the design of the indigenous reactors (or with the quality control issues pertaining to their components)—usually after construction is already underway or complete—has added to the delays experienced by the nuclear power program (sometimes resulting in reactor shutdowns), with the subsequent remediation efforts further exacerbating the cost penalties.[17] Occasionally, the difficulties in securing reliable access to fuel also played a role in reducing the capacity factor of various operating Indian nuclear plants.[18] Thanks to a combination of such factors historically, the DAE's reactor program was unable to offer the Indian consumer electricity at a sufficiently competitive rate in comparison to other energy sources and, as a consequence, successive Indian governments did not invest in nuclear power production as a national priority even if they were cognizant of its importance.

In the future, however, nuclear power in India *may* yet find a second chance to redeem itself. Prime Minister Narendra Modi has ambitiously announced the objective of transforming India into a developed country by 2047, the centenary of India's independence. Realizing this goal, labeled "Viksit Bharat" (Developed India), will require India to at the very least sustain double-digit economic growth rates consistently (or at least approach them) for another quarter century.[19] Achieving any economic expansion of this magnitude will require significant new sources of energy—which cannot involve simply doubling down on fossil fuels because Modi has also committed India to a target of net zero emissions by 2070.[20]

Given these twin targets, one analyst has summarized India's energy predicament succinctly in the following terms.[21] India's demand for power in 2022–23 stood at 1,503 billion units (BUs). This demand was satisfied by an installed power generation capacity of 415.4 GW, with fossil fuels providing 236.68 GW of power and renewables providing 171.8 GW. On the assumption that India could need some 5,921 BUs of power by 2050, the country would require as much as 4,000 GW of installed energy generation capacity. India has made great headway in recent years by investing in renewable energy sources,[22] but given the variability of renewables such as solar and wind energy, the hidden subsidies associated with these investments, the still-significant challenges of storing renewable energy, and the frequency variations that complicate the utilization of renewable energy in industry, all conspire to make renewables—however desirable—less than ideal sources of baseload power.

If Modi's ambitions to make India a major semiconductor manufacturing center, a significant producer of green hydrogen, a generator of sophisticated indigenous artificial intelligence (AI) models, and an example of the benefits flowing from the large-scale shift toward electricity for transportation are to be realized—at a time when urbanization in India is rapidly increasing and climate change will increase the need for air conditioning dramatically—the Indian demand for increased quantities of reliable baseload power will only grow by leaps and bounds. In any event, India plans to increase the share of renewables in its energy basket substantially in the years to come.[23] But because the energy that can be potentially sourced from renewables is currently estimated at no more than 1,000 GW, the balance—some 3,000 GW (or seven times the current installed capacity)—will have to derive from both fossil fuels and nuclear power, if India's economic and climate mitigation goals are to be met by around mid-century.[24]

Even the more granular assessments of India's renewable energy potential do not transform this basic conundrum. For example, India's National Institute of Solar Energy estimates that the country's solar energy potential subsists at around 748 GWp (gigawatts-peak). India's wind energy potential at a hundred meters above ground level is estimated to be about 302 GW. Including large hydropower plants, India's hydropower potential is assessed at something around 145 GW. And India's biomass potential is about 25 GW. When aggregated by these discrete sources, India's renewable energy potential then turns out to be about 1,220 GW.[25] Even if it is assumed that technology improvements over the next several decades will expand these numbers somewhat, say to 1,500 GW, the broad magnitudes suggest that India will need anywhere from at least 2,500-2,780 GW of other installed power generating capacity.

Clearly, in these circumstances, fossil fuels will still remain the dominant sources of energy for India even in 2047 and immediately beyond. But nuclear energy will have to make unprecedented contributions if Modi's successors are to achieve the goal he has set for the country over the next few decades. The most detailed analysis of this challenge conducted in India offers some sobering conclusions.[26] On the assumption that India will continue to enjoy medium levels of economic growth indefinitely, a team of scholars at the Indian Institute of Management (IIM), Ahmedabad, has estimated that—in comparison to the currently installed nuclear power generation capacity of 7.4 GW—a net zero strategy that emphasized nuclear power would require 265 GW of installed capacity by 2050; a strategy that emphasized either fossil fuels with carbon capture or renewables would still require 75 GW of installed nuclear power capacity; and an integrated strategy that balanced all energy sources optimally would require 95 GW of installed nuclear capacity by 2050. Even at the lowest values, therefore, this study suggests that an order of magnitude increase in nuclear power generating capacity would be required by 2050 if India is to reach the economic *and* environmental targets that Modi has ambitiously laid out for his country.

On current trends, this arguably lies beyond the DAE's reach, if the past record is anything to go by. Even if it is assumed that India's atomic energy program has by now passed the kinks in the learning curve, it is difficult to imagine that domestic reactor construction can ramp up rapidly enough to meet targets of the sort identified above. A few numbers help to place the challenge in perspective. If all the reactors currently under construction in India are added to those already operating, India will have about 13 GW (or at best some 14 GW) of installed nuclear capacity by around 2030. The DAE/NPCIL had set for itself a target of some 22 GW of installed nuclear capacity by 2030-31.[27] Toward that end, ten 700-MWe indigenous PHWRs were supposed to be constructed "in fleet mode" (meaning concurrently rather than sequentially), and four Russian light water reactors (LWRs) of 1,000-MWe (Kudankulam Nuclear Power Plant Units 3-6) were to be added as well. The pace of construction thus far, however, suggests that while the four Russian reactors will probably be commissioned by about 2030, only four of the ten indigenous PHWRs will likely be operational by around that time. As a consequence—if all goes well—India could have about 14 GW of installed nuclear capacity by the end of the current decade rather than the 22 GW that the DAE/NPCIL has been pursuing.

If building eight reactors during the current decade is proving to be so taxing, it is unclear how India's indigenous nuclear power program can satisfy the demands identified by the IIM study referred to earlier. Aiming for 75 GW of total installed nuclear capacity would require an additional 87 or so 700-MWe indigenous reactors (if India already has 14 GW of installed nuclear capacity by 2030), or some 115 700-MWe plants if New Delhi seeks to achieve the 95 GW of installed nuclear capacity required by the balanced energy strategy. Building higher output reactors eases the problem somewhat but does not transform it. Even if India were to pursue the 1.65-GWe European Pressurized Reactors (EPRs) currently offered by France to meet such targets, it would have to construct between 36 and 49 new reactors within a space of two decades to meet the 75 GW and 95 GW targets respectively. Given the immensity of the challenges involved here, a nuclear-heavy net-zero strategy that contemplates creating 265 GW of installed nuclear capacity then simply borders on the fantastic and must be ruled out tout court.

Pursuing even the more modest—yet still ambitious—targets will be difficult for multiple reasons. For starters, it is simply not clear whether the domestic component suppliers could keep up with such expanded demand within the timeframes involved even if government financing were to be made available. And thus far financial support for reactor construction from the Government of India has not been exceptionally generous. What complicates matters further is that the DAE and its adjunct, NPCIL, have expertise largely in building PHWRs of different sizes and not the more common kinds of high-output LWRs, not to mention the new kinds of small modular reactors (SMRs) that Indian policymakers are hoping could become retrofitted substitutes for their decommissioned coal plants.[28]

If India pursues SMRs, as it currently seems inclined, there will be no alternative for New Delhi but to welcome significant foreign participation in its nuclear power program.[29] The same will be true if any large-scale expansion of nuclear power is to occur in India. Consequently, the Indian government has already taken initial steps in this direction by collaborating with Russia's Rosatom, the state nuclear energy corporation, in setting up six large, 1,000-MW VVER-1000 reactors at Kudankulam.[30] India is simultaneously negotiating with France for the construction of six 1,650-MW EPRs at Jaitapur.[31] These negotiations have slowed because of issues relating to financing and liability—problems that are even more conspicuous in the case of U.S. nuclear suppliers who have thus far stayed out of the Indian nuclear power market. Consequently, the Indian government's approval "in principle" for the construction of up to twelve new U.S. nuclear reactors at Mithi Virdi and Kovvada is nowhere near fructification.[32]

All the same, the scale of India's needs for new installed power capacity is so high that New Delhi will not enjoy the luxury of choosing between domestic and foreign reactor suppliers or between large or small reactors. It will need them all if it is to meet its ambitious economic and climate mitigation targets simultaneously. Unlike in the United States, where electricity consumption and GDP growth have diverged after about 1996 primarily because of changes in the structure of the economy, the increases in energy efficiency, and new innovations in energy pricing, electricity availability, access, and use in India remains strongly correlated with, and in fact stimulates, economic growth and development.[33] Some studies suggest a bidirectional causal relationship between electricity consumption per capita and per capita growth of the gross domestic product.[34]

The evidence from India and elsewhere thus seems to confirm the expectation that New Delhi's growth ambitions alone will require increased electricity generation capacity, with its manufacturing, transportation, AI, space cooling, and climate adaptation goals further intensifying this demand. These realities could give India's nuclear power sector a new viability if its national leaders and its nuclear establishment play their cards right. Realizing this aim, however, will require three major transformations simultaneously—changes that demand deeper and more systematic thinking.

An Ideational Transformation

The first transformation that will be necessary to shift India's nuclear estate on to a sustainable expansion has nothing to do with either resources or technology. Rather, it requires a shift in mindset and specifically a willingness to look beyond Homi Bhabha's legendary three-stage nuclear program that has served as the bedrock of the DAE's institutional ethos, if not its raison d'être, since its founding.

Bhabha's three-stage program was conceived in the 1950s when, in the aftermath of the Second World War, nuclear energy in both its civilian and military applications constituted *the* frontier of advanced technology. For India, a newly independent nation that harbored dreams of greatness, domesticating nuclear technology—by achieving mastery over the entire fuel cycle—was judged to be essential even though the great powers were likely to protect their atomic secrets for reasons of both national security and commercial interests. Then U.S. president Dwight D. Eisenhower's momentous "Atoms for Peace"[35] initiative opened the doors for India to receive Western nuclear technology, and New Delhi welcomed these benefits because it enabled India to climb the technology ladder and build domestic capabilities that would eventually diminish its dependence on foreign states.

In this context, Bhabha was acutely aware of India's potential nuclear fuel resources. Recognizing that the country possessed only minuscule quantities of uranium ore but was blessed with the world's largest thorium reserves, his brilliant three-stage plan—which was first publicly presented in 1954 and formally adopted by Nehru's government in 1958—was intended to secure India's energy independence by exploiting its modest uranium holdings through technological pathways that would eventually permit it to utilize its vast thorium reserves to create abundant nuclear energy.

Shorn of all technical complications, the three-stage plan envisaged progress along the following sequence.[36] In Stage 1, a series of Canadian-designed and constructed PHWRs (that would be later indigenized) would use the scarce natural uranium as fuel to produce electricity while also producing plutonium (Pu-239) as a byproduct. Stage 2 required the construction of fast neutron reactors. In the early phase, these breeder reactors would use the Pu-239 and the fertile uranium-238 (U-238) recovered from the spent fuel expended from the Stage 1 PHWRs to convert the U-238 to produce more Pu-239. In the later phase, these Stage 2 breeder reactors would burn the produced Pu-239 to breed a uranium isotope, U-233, in the thorium (Th-232) fuel blanket that surrounds its core. Stage 3 required the development and construction of advanced heavy water reactors (AHWRs): these reactors would burn the U-233 produced in the Stage 2 plants in their cores surrounded by a Th-232 blanket and thereby exploit the ensuing nuclear reactions to generate two-thirds of their output from Th-232 itself.

Through such a design, Bhabha sought to use the modest quantities of notionally available Indian uranium ore to produce plutonium to then breed U-233 from India's plentiful thorium—before finally utilizing the U-233 and thorium in combination in the AHWRs to produce huge quantities of energy from thorium itself. Since the Stage 2 breeder reactors are intended to produce more plutonium than they consume, and since India has enormous thorium reserves, the Stage 3 facilities that are conceived by the DAE today could in principle produce 358,000 GWe-years of electricity, which would satisfy India's energy requirements in ways that its meager uranium reserves could never do even if they were most efficiently utilized in a "once-through" fuel cycle involving PHWRs alone.[37] This vision remains the grand architectonic that animates the DAE to this day.

Unfortunately for India, progress has been agonizingly slow.[38] Although the Stage 1 PHWRs have been widely constructed in India, they have turned out to be costlier than initially imagined for the reasons described earlier. The Stage 2 breeders—of which only one intended for commercial operation, the Prototype Fast Breeder Reactor (PFBR), has been constructed—are still far from technical, let alone economic, maturity. And the Stage 3 reactors are as yet only a gleam in the eye, which makes commercial thorium-based nuclear power generation in India (and perhaps in the world as well) at least many decades away.[39]

But delays are not the only casualty afflicting the three-stage plan. There are fundamental technical problems that Bhabha could not have foreseen when he developed his solution because these became apparent only after he had passed. The hardest challenge pertains to the extraction of U-233 from thorium in the later-phase Stage 2 breeder reactors: this is vital to the three-stage plan because the extracted U-233 is what enables thorium to be used on an extensive scale in the Stage 3 AHWRs to produce large quantities of electricity from the element that India has in great abundance.

Yet the difficulties are multifarious. To begin, thorium dioxide is much harder to dissolve in acid than is uranium dioxide, meaning that it is harder to recover the U-233 from thorium than it is to recover plutonium from irradiated uranium. What is worse, the U-233 is invariably contaminated with U-232. The first decay step of U-232 produces Thorium-228 (Th-228), which further decays to produce other daughters including the intensely hot and highly penetrating gamma emitters, Bismuth-212 (Bi-212) and Thallium-208 (Ti-208).[40] Though the U-233 is initially not very radioactive, the buildup of these elements quickly makes the U-233 so hot that it can only be handled remotely in shielded facilities, greatly complicating the production of fresh U-233 fuel. Finally, the recovered thorium is also highly radioactive since it is contaminated by Th-228. Although Th-228 has a half-life of only 1.9 years—in contrast to the 69-year half-life of U-232—the recovered thorium still has to be stored for "sufficiently long" periods of time, some "10 to 20 years," before any U-233 extraction can begin.[41] This is because waiting five half-lives (9.5 years) only reduces the radiation by a factor of 32, whereas waiting for ten half-lives (19 years) reduces a radiation by about a factor of 1,000. The long waiting times involved in outliving the process of Th-228 decay then imply that a significant fraction of the thorium in a U-233 breeder reactor fuel cycle will be in storage waiting for the radiation to abate rather than being available for fueling reactors.

Even when the thorium is finally available, however, the extraction of U-233 and its fabrication into fuel requires heavily contained (and costly) facilities that necessitate remote operator handling. Because the value of such investments on a commercial scale is still dubious, there are as yet no facilities supporting the extensive deployment of thorium-based fuels anywhere in the world. Even India has experimented with separating U-233 from irradiated thorium only under laboratory conditions, and if the most recent DAE annual report is anything to go by, there seems to be currently no serious effort underway to develop a reactor fueled with U-233, which could be partly a consequence of the lengthy time it has taken to bring the PFBR into operation.[42] Indeed, the DAE has not even proposed the design of a U-233 breeder reactor, only the AHWR, which emphasizes energy production from thorium.

Extracting U-233 from thorium in sodium-cooled molten salt reactors (as opposed to a notional solid-fueled breeder reactor) admittedly helps to address another less challenging problem: separating the intermediate isotope, protactinium (Pa-233), which if left in the reactor beyond its estimated 27-day half-life, can transmute the desirable U-233 isotope into the inutile U-234.[43] But even this solution does not solve the larger difficulties of separating the U-232 contaminants from the U-233 that is essential for exploiting thorium to produce nuclear energy in India's Stage 3 reactors.

At the end of the day, there is no escaping the fact that, as one International Atomic Energy Agency (IAEA) report summarized it, "significant financial outlays will be necessary" if thorium-based nuclear power is "to reach the same large scale industrial status already reached with [the] U/U-Pu [Uranium/Uranium-Plutonium] fuel cycle."[44] Given the easy availability and low cost of natural uranium, the widespread accessibility to low-enriched uranium, and the oversupply of plutonium from commercial reactors globally, utilizing thorium-based fuels in the manner envisaged by India is likely to remain highly unattractive from both technological and commercial perspectives for a long time to come.

To be sure, if India is willing to expend the resources necessary, the appropriate technical solutions to the problems of the thorium fuel cycle can be found—but the economics of investing in these fixes today is more questionable than ever for at least two reasons.

For starters, the autarkic impulses that underlay Bhabha's design when it was developed are no longer justified because atomic energy, outside of its military applications, is no longer a frontier technology that states wish to preserve at all costs. The commercialization of nuclear energy over the years has resulted in even advanced nuclear power generation technologies residing in private hands, and these are now available to any legitimate recipient willing to participate in the marketplace.[45] India, therefore, does not need to rely on bespoke indigenous solutions to produce nuclear power. Instead, focusing on run-of-the-mill nuclear technologies that it has already perfected, such as PHWRs, while supplementing those with other orthodox solutions, such as LWRs, can greatly increase the share of nuclear power in India's energy mix if New Delhi is willing to create the conditions for expanded markets in India.

Equally and perhaps more pertinent is the fact that the fundamental constraint that triggered the creation of Bhabha's three-stage plan—the shortage of Indian natural uranium ores—has effectively disappeared as a result of then U.S. president George W. Bush's landmark 2005 nuclear deal with India's then prime minister Manmohan Singh.[46] This agreement, by enabling India to enter the international nuclear market while imposing no constraints on its nuclear weapons program, has removed the limitations imposed by its small uranium holdings: India can now buy as much uranium as it needs to fuel its current and future reactors from foreign sources at likely cheaper prices than mining it at home. This implies that India really has no need for exotic and expensive solutions like fast breeder reactors and thorium-fueled AHWRs. Instead, it can standardize on conventional nuclear power plants such as PHWRs and LWRs, which use now freely available natural and low-enriched uranium respectively, to produce as much nuclear electricity as market conditions permit.

The critics of this argument will immediately point to the fact that the United States could cut off nuclear fuel supplies to India at some point in the future if, for example, India were to pursue policies, such as testing nuclear weapons, that Washington might dislike.[47] But this criticism is not persuasive for several reasons. The United States today enjoys a relationship with India that is quite unlike that which persisted during the Cold War. Far from being a threat, India's nuclear weapons are now perceived as a de facto asset by Washington.[48] While a return by India to hot testing could—not will—momentarily perturb the United States depending on the larger geopolitical environment, U.S. policymakers are unlikely to respond with sanctions and fuel cut-offs as they did in yesteryears. In fact, during the debate on the Hyde Act, the legislation that restored U.S. nuclear cooperation with India, the U.S. Senate explicitly rejected an amendment that required Washington to cut off nuclear cooperation with India in the event of a future Indian nuclear test.[49]

Even more to the point, however, George W. Bush's greatest bequest to India was that he did not sign merely a bilateral nuclear cooperation agreement with New Delhi—as China later did with Pakistan—but integrated India into a wider circle of international nuclear cooperation by lobbying the Nuclear Suppliers Group (NSG) to grant India an exemption from full -scope safeguards.[50] As a consequence, even if the United States were to terminate the supply of nuclear fuel to India in the event of a future crisis, New Delhi could continue to purchase the same from many other national suppliers who may not follow Washington's lead or from countries such as Niger or Uzbekistan that are not members of the NSG.[51] The bottom line, therefore, is that between stockpiling fuel reserves and access to various independent national suppliers—both routes currently pursued by New Delhi—India can comfortably expand its nuclear power program on the strength of imported uranium without any peril to its viability in all realistic circumstances.

Pushing along in this direction, however, will require the current Indian government to move away from the commitment its predecessor had made to the three-stage program in 1958. It is not clear that even a bold political leadership, such as Modi's, would be willing to take such a step. The DAE, which by now has Bhabha's three-stage plan encoded in its institutional DNA, is even more unlikely to renege on the vision that has defined its institutional existence for some seventy years. Both entities, however, have in practice recognized that Bhabha's original conception is at best a distant dream, as evidenced by the decision taken in the 1990s to import LWRs from foreign sources.[52]

This shift, which combines indigenous PHWRs and imported LWRs, should give India's nuclear energy sector significant breathing room. And since natural and low-enriched uranium fuel can now be readily imported by India, there is no reason why New Delhi should look beyond this modified Stage 1 iteration to expand nuclear power within the country. This does not imply that India should simply give up on its breeder program. This has been suggested sometimes because of, among other things, safety issues and because India may lack the plutonium necessary to fuel these plants in the numbers planned.[53] If the availability of plutonium is not an issue, however, India could use its planned breeders to produce more plutonium (assuming that it can successfully undertake metallic fuel fabrication and the reprocessing of such fuels on a commercial scale in the interim) for eventual use in mixed oxide fuels to power both its PHWRs and LWRs. In principle, this could decrease the environmental burdens of storing excessive amounts of high-level radioactive waste while more efficiently utilizing the uranium isotopes originally contained in the fuels that power India's PHWRs and LWRs.[54] Given the relatively low price of natural uranium and arguably that of low-enriched uranium as well, it may be cheaper for India to forego breeding additional plutonium and accept the cost of storing high-level wastes, thus maintaining the current PFBR mainly as a science and technology experiment rather than as the spearhead of a viable commercial proposition.[55]

The possibilities for rapidly expanding the share of nuclear power in India's energy basket—the crying need of the moment—will depend in the final analysis, however, fundamentally on how they meet the market test and, beyond the ideational transformation necessary to support this goal, will require an institutional transformation of India's nuclear estate as well.

An Institutional Transformation

The biggest challenge facing the expansion of nuclear power in India is the exorbitant upfront cost of nuclear reactors. What complicates matters further is that NPCIL has neither standardized on a single reactor design nor developed a sufficiently high-output reactor that eases the capital costs of the constructed plants. This legacy is owed to India's troubled nuclear history: when the Canadian suppliers of India's early PHWRs left the country in the aftermath of its 1974 nuclear test—an event that jumpstarted the contemporary nonproliferation system[56]—the DAE was left with two completed 160-MWe LWRs constructed by the U.S. General Electric (GE) company at Tarapur and one barely completed 220-MWe PHWR constructed by the Canadian government-owned nuclear science and engineering company, Atomic Energy of Canada Limited, at Rawatbhata in Rajasthan.

This 220-MWe PHWR at the Rajasthan Atomic Power Station (RAPS-1) provided the baseline design for India's subsequent, indigenously constructed, PHWRS, which form the mainstay of its Stage 1 program. Completing the two reactors in Rajasthan (RAPS-1 and RAPS-2) provided the DAE with a painful learning-by-doing experience. Although ultimately rewarding, in that it enabled India to acquire mastery over the plutonium fuel cycle, it also left the DAE with a succession of reactor designs. As India became more confident in building 220-MWe PHWRs, it scaled up to building 540-MWe plants, which ultimately concluded in a 700-MWe design, the first reactor of which started operation in 2021. The DAE has also begun to develop a 900-MWe reactor—based on a further upscaling of its 700-MWe design—but no PHWR of this size has as yet been constructed in India.[57] Today, there are fifteen 220-MWe, two 540-MWe, and two 700-MWe indigenous PHWRs, in addition to two U.S.-origin 150-MWe and two Russian-origin 1,000-MWe LWRs, operational in India. Two more indigenous 700-MWe PHWRs, four more Russian-origin 1,000-MWe LWRs, and one indigenous 500-MWe fast breeder reactor are currently under construction.

The largest indigenous nuclear reactor built in India thus does not exceed 700-MWe in output and it is sometimes argued that India should standardize this design and build it in large numbers in order to gain economies of scale.[58] Given the high upfront capital costs of building nuclear reactors, however, it is unclear whether settling on a 700-MWe design is beneficial when 1,000-MWe output (or higher) reactors are routinely constructed the world over. The Russian VVER-1000 reactors at Kudankulam already represent such an example, and France's proposal to build six 1,650-MWe LWRs at Jaitapur in Maharashtra, could represent even greater economies. Because reactor-life-extension programs have proven to be extraordinarily successful in recent years, the longevity of a nuclear reactor could extend to as many as eighty years, thus making the amortization of a high-output reactor's costs much more attractive.[59]

The longer a reactor remains operational, the cheaper the electricity produced since the variable costs incurred after construction involve mainly maintenance and fuel, both of which are relatively inexpensive. It is estimated, for example, that the tariff for electricity in 2017 from the oldest commercial reactors built in India—the GE-constructed TAPS 1 & 2—came in at about 1 rupee per kilowatt-hour, which is lower than the lowest cost of solar power in India.[60]

The lesson is clear. For nuclear power to expand in India, the largest output nuclear reactor designs available should be constructed as quickly as possible without compromising safety. The financing to sustain such expansion will have to come from both government and private sources, and the likelihood of such financing becoming available increases in the first instance if the entities involved in the construction and operation of these reactors have a credible history of successfully executing large, high-quality, power projects.

In this context, it is not only the reactor's output that bears on its cost-effectiveness but possibly its design as well. India's indigenous power reactors are not only relatively low-output plants, but they are also PHWRs. Homi Bhabha had settled on these reactors early on because his three-stage plan was intended to preserve India's nuclear weapons option even as it sought to maximize the production of nuclear electricity. PHWRs served that purpose splendidly because they did not require the use of imported enriched uranium, thereby permitting some of these reactors to avoid being placed under safeguards, and because they produced weapons-usable plutonium as a natural byproduct of producing power. But PHWRs are arguably inherently uneconomical because they require heavy water as a moderator and coolant to support the use of natural uranium as the reactor fuel.[61]

Given India's choice of PHWRs as the mainstay of its power program, New Delhi has been compelled to enlarge its heavy water production to match the expanding number of its indigenous reactors. Scarred by past shortages, India has in fact been overproducing heavy water during the last three decades.[62] The cost of this effort is substantial, and it only adds to the high price of nuclear power in India. Thanks to path dependency, however, India's indigenous program is now locked into PHWRs more or less permanently, and comments by the DAE's leadership suggest that India's imported LWRs are viewed mainly as supplements, with their low-enriched uranium fuel supporting the DAE's existing plans for reprocessing within a closed fuel cycle.[63]

In any event, it is unfortunate that NPCIL has had a difficult time in completing its PHWR construction programs consistently on schedule, albeit not always because of problems of its own making. The reasons for its troubles are complex and implicate multiple players. For starters, NPCIL is a nuclear power plant operator whose competence centers largely on running DAE-designed reactors. Although it is involved in constructing these power plants, it is fundamentally a systems integrator that relies on various public- and private-sector manufacturers to produce their various components. The weaknesses of the component suppliers, as evidenced by their problems with delivering sub-systems on schedule, can be attributed to their technological and industrial inadequacies as well as their inability to retain qualified personnel in the face of limited or inconsistent orders from NPCIL.

These problems, in turn, are caused by the larger funding constraints, which create cascading effects that contribute to NPCIL's relatively poor performance and, consequently, depress its earnings. This creates a vicious regress that only exacerbates the overall problem.[64] In the face of such tribulations, NPCIL's greatest failure has perhaps been its proclivity to issue wildly unrealistic projections about the expansion of nuclear power in India, a pathology that is intensified by the imperatives of playing to the political gallery in order to protect its organizational interests given its substandard performance. Consequently, if the Indian nuclear power program is to flourish, India will have to look for alternative strategies to complement NPCIL's activities.

The Modi government took an important step in this direction in 2022 when it permitted NPCIL to jointly develop nuclear power plants in partnership with the National Thermal Power Corporation (NTPC), the public sector entity that builds and operates fossil-fueled and renewable energy power plants across the country.[65] Because NTPC is the largest power-generating company in India, with long experience in the design and execution of complex projects as well as in raising funds in capital markets, collaboration between the two entities is anticipated to lead to more rapid reactor construction. The two companies have already signed an agreement to build two new nuclear complexes in Madhya Pradesh and Rajasthan, with two 700-MWe and four 700-MWe reactors in each location respectively.[66] Although these are still smaller reactors than are ideal—chosen because they represent the state of NPCIL's current art—this approach nonetheless offers some promise over the previous strategy of NPCIL going it alone.

In the July 2024 national budget, the Modi government sprung another surprise when, moving beyond the current public-public model of collaboration to support nuclear power expansion, it called for new public-private partnerships to develop small modular reactors (SMRs) of ≤300-MWe as a complement to the existing arrangements centered on constructing large (≥700-MWe) conventional reactors. Although the economics of SMRs are still unclear in the Indian context, it makes eminent sense to explore their acquisition, especially if they can be cost-effectively substituted for the old coal-fired electricity plants whose retirement India has been delaying for want of appropriate replacements.[67]

There are several foreign companies such as Westinghouse, NuScale, Holtec, and Rosatom that are actively involved in SMR development, with Holtec in particular, offering an extremely innovative design that has been selected to revitalize the 800-MWe Palisades Power Plant in Covert Township, Michigan, in the United States. The challenges of land acquisition and the availability of water in India are specifically mitigated by Holtec's design, which employs a smaller physical footprint and does not require proximity to a water body for its operation.[68] These land use advantages coupled with advanced passive safety features apply to many kinds of SMRs, whose designs open the possibility of hybrid systems that synergize nuclear power with renewables. Hence, it is not surprising that the Indian government wants to explore their utility in an expanded Indian nuclear power program.

How quickly SMRs can be brought to fruition in India remains an open question. Even Holtec's design may take many years to construct and begin operations. A purely turnkey project might be more economical and more efficient, but given India's fixation with domesticating advanced technology the Modi government might encourage the entry of foreign SMR companies into India mainly to forge bilateral collaborations aimed at developing its own marquee "Bharat Small Modular Reactors."[69] If this turns out to be the case, or if India chooses to go down the indigenous development path entirely, the appearance of SMRs in the Indian nuclear power program will take even longer to materialize.[70]

Nonetheless, the new institutional innovations announced in Modi's budget—public-private partnerships in the Indian nuclear energy sector—are altogether welcome, but they are still unduly conservative.[71] Nuclear power for electricity production no longer subsists at the "commanding heights" in modern economies. In many countries where nuclear energy contributes a substantial share of the power basket, such as the United States and Japan, nuclear reactors are built and operated by private entities. Although there are conspicuous examples to the contrary, such as France and South Korea, the dominant trend in India over the last thirty-some years has been the shift in priority toward the private sector and thus there is no reason anymore why nuclear power production should be the exception to this rule.

In fact, the experience of Modi's June 2020 decision to open the space sector to private enterprise—which, like atomic energy, was previously under exclusive government control—is instructive. This decision has since transformed India's space endeavor, fueling innovation, reducing costs, and creating new productive linkages between state and industry.[72] As such, it should also serve as the model for reforming the nuclear power sector, which could thrive in similar ways in the years to come even after accounting for all the relevant differences.

A key element of institutional reform going forward, therefore, should be the opening of India's nuclear power sector either to private-private collaboration, where private Indian companies collaborate with private foreign partners through joint ventures to build and operate nuclear power plants, or to straightforward private participation, where Indian or foreign entities invest in wholly owned ventures to construct nuclear plants on a turnkey basis or to build and operate such facilities depending on their competence and their assessment of profitability. Opening the nuclear sector to private investment remains another example of the unfinished business pertaining to India's economic reforms and it is likely that, just as in the space sector, liberalized access here would attract Indian and foreign majors *if* this innovation is complemented by other, much needed and often long-overdue, reforms in the country's electricity market.[73]

If India is to satisfy its ambitious 2047 objectives of becoming a developed country while minimizing the costs imposed by climate change along the way, expanding non-polluting modes of electricity generation through, among other things, increased investments in nuclear energy will be essential—and this objective, like so many others, is best realized by inviting private participation in India's nuclear power sector against the backdrop of creating more efficient markets across the economy as a whole.

Such an institutional transformation will require the Indian government to restructure the DAE's role as India's nuclear power enterprise evolves. Rather than being deeply involved in every aspect as it is now, the DAE should encourage other nonaffiliated entities to take the lead in power generation while it focuses on the six areas where it has—and should preserve—its comparative advantage:

- program planning, which, assuming that the ideational transformation discussed earlier is completed, would ensure the orderly evolution and oversight of the nuclear sector as a whole;

- defining standards in diverse dimensions, to include the certification of nuclear reactor designs and their safety requirements;

- managing security, to include oversight of both the physical safekeeping of plants and the reliability of personnel, which will need to be better rationalized in a system that includes private and public entities together;

- training of nuclear operators, which eventually could become the province of private entities, including universities and private plant operators, but should still be certified centrally and uniformly by the DAE;

- advanced research and development, especially of alternative fuel cycles, fusion power plants, and other civilian applications of nuclear energy such as in agriculture, medicine, and space exploration, mainly to push the envelope of human knowledge in areas where private actors are unlikely to make the requisite investments based on concerns about profitability;

- and, finally, the weapons program, which for self-evident reasons must remain under state control and hitherto has not received the attention it deserves even within the nuclear establishment, given the dramatically increased threats now posed by China and Pakistan to India.

An institutional evolution of this sort would still leave the DAE in the cockpit, with responsibility for managing India's nuclear energy sector. But the thrust of the power program would increasingly be provided by private actors who, again in principle, could be involved in everything from the mining and milling of nuclear fuel to its disposal—as evidenced by the international presence of Australian, Canadian, French, and American companies in these activities—to the benefit of the larger Indian nuclear enterprise and the country as a whole. Bringing this vision to fruition, however, requires a third element, the legal transformation that completes, and is a necessary complement to, the ideational and institutions transformations discussed previously.

A Legal Transformation

The legal transformation necessary to accommodate the entry of the private sector into India's nuclear power generation program arises from the constraints imposed by the Atomic Energy Act of 1962, as amended by the Atomic Energy Act of 1987, which reserved all activities in this arena exclusively for government companies.[74] Amending the act to permit private sector participation, in principle, in all stages of the nuclear fuel cycle will be necessary even though as a practical matter private actors are most likely to invest mainly in building and operating reactors and in some derivative activities, such as managing spent fuel storage, in the near term. All the same, amending the Atomic Energy Act—especially its Sections 3 and 22—to ensure the private sector's widest participation in the entire fuel cycle is necessary if India is to successfully stimulate nuclear power generation through domestic and foreign investments in the decades to come.

Although the legal transformation required for this purpose will have to address myriad issues, the importance of three broad changes stands out. The first is organizational. A significant expansion of the Indian nuclear sector will require New Delhi to pay increased importance to safety. Although nuclear power plants are ordinarily safe facilities, ensuring their sound operation requires regulatory and oversight institutions that India currently does not possess. The Atomic Energy Regulatory Board (AERB), which is responsible for ensuring the safety of India's nuclear program, has too many institutional affinities to the DAE, the body whose assets it is supposed to be supervising.

There have been numerous instances in the past when the latter has exercised undue influence over the regulator, leading the Comptroller and Auditor General of India to conclude that the AERB "is not a legal entity and is merely a subordinate authority" to the DAE and, as such, "has no effective independence as per the criteria laid down by [the] IAEA."[75] Making the AERB fully autonomous of the DAE must, therefore, become one of the key objectives pursued by any future amendment of India's Atomic Energy Act.

The safety of India's nuclear estate, however, cannot be entrusted solely to legal reform; it requires equally political and public vigilance. Because the AERB, at least in the near term, will likely be composed of individuals whose careers are rooted in DAE establishments, nurturing a culture of genuine independence will admittedly be challenging. As the Indian nuclear sector matures, however, this problem may be progressively mitigated because nuclear engineers who have trained in the private sector and have a history of operating power plants not owned by NPCIL, could when serving on the AERB demonstrate a freedom from DAE influence that many of their predecessors may not have had. While these problems must be managed by political and public scrutiny in the interim, there is absolutely no alternative but to begin by guaranteeing the independence of the AERB by statute and making its responsibility to develop and enforce safety regulations a binding legal obligation.[76]

The importance of political responsibility for India's nuclear program highlights another serious deficiency in the current Indian decision-making structure, namely, the absence of any external review bodies that can evaluate India's nuclear activities and offer the prime minister impartial advice on programmatic decisions. The Atomic Energy Commission, which is the apex body that formulates policies and programs implemented by the DAE and its various subsidiary organizations, is composed of senior bureaucrats and other individuals, most of whom have close links with (or have with risen from within the ranks of) the atomic energy establishment.[77]

As such, they all have significant stakes in the inherited program, with the technologists among them committed to its viability while the others lack the technical competence to assess the established preferences or to offer alternatives. This weakness became particularly apparent during the negotiations pertaining to the U.S.-India Civil Nuclear Agreement, when Indian policymakers had no recourse to any external (institutional) expertise that could be drawn upon to help them evaluate their choices. A similar lacuna became visible when the debate over the success of India's thermonuclear weapons surfaced in the aftermath of its 1998 nuclear tests. Although there were protagonists on both sides of this issue from within the nuclear and defense establishments itself, India's civilian leaders had no independent means of evaluating the conflicting claims despite their importance to national security.[78]

Creating a statutory external review board composed of diverse experts who can advise the prime minister on matters pertaining to nuclear energy, therefore, ought to be seriously considered as part of the organizational reform of India's nuclear sector. That said, the challenge of finding suitable candidates to staff such a body—when there are genuinely few individuals with expertise in nuclear science outside of the government—cannot be overstated.

The second aspect of the legal transformation relates to the management of nuclear fuel. Although nuclear energy is now commonplace in modern economies, it is still unique because of the intimate relationship between the nuclear fuel cycle and the production of nuclear weapons. Thanks to this affinity, the nuclear reactors used to produce power are safeguarded through national agreements with the IAEA and their associated fuel chains are protected through monitoring of the flow of materials, accounting of the material balances, and the surveillance of the physical facilities to prevent any diversion to a weapons program.[79] For non-nuclear-weapon states, the safeguards relating to the fuel cycle are particularly important, but the integrity of the safeguards system depends equally on preventing the diversion of nuclear materials within weapon states from voluntarily safeguarded facilities.

As long as the Indian nuclear power program resides entirely in the public sector, the protection of the fuel cycle is ensured simply through a national agreement between the Government of India and the IAEA. But as the Indian nuclear industry opens up to private participation, India's Atomic Energy Act will have to be amended to address various issues relating to the nongovernmental ownership of fuel, its storage and possible reprocessing, and its eventual disposition—to include the role of the IAEA in these matters. The relationship between the existing system of nuclear waste management and the possibly private sector-owned spent fuel stockpiles will also have to be redefined in law, and there may also be need for a new reactor decommissioning authority to oversee the retirement of privately owned nuclear plants. Permitting the entry of private actors into India's nuclear power sector will spawn numerous new issues that must be addressed either in law or in practice, but the process of reviewing how the Atomic Energy Act should be amended ought to begin now.[80]

Finally, the third—but not the least—important legal transformation that will be necessary to induce meaningful private participation in India's nuclear power generation program will be reforming the Civil Liability for Nuclear Damage Act (CLNDA) of 2010.[81] The CLNDA, which in contravention of international norms that require liability for nuclear accidents to be channeled solely to the operator of a nuclear plant, added a right of recourse in Section 17(b) of the Act that permitted the operator to seek compensation from a nuclear supplier in case of accidents resulting from "an act of supplier or his employee, which includes supply of equipment or material with patent or latent defects or sub-standard services."[82] This complication is exacerbated by another ambiguity in Section 46, which states that "the provisions of this Act shall be in addition to, and not in derogation of, any other law for the time being in force, and nothing contained herein shall exempt the operator from any proceeding which might, apart from this Act, be instituted against such operator."[83]

Consequently, as one authority noted, "it could be argued that under the broadly phrased Section 46, a victim of a nuclear incident could bring a liability claim against the operator in court under tort law, and possibly even include the supplier as a codefendant. This possibility seems to directly undermine the long-standing principle of legal channeling and is at odds with the Preamble of the Liability Act which states that it is an Act to provide for 'civil liability for nuclear damage and prompt compensation to the victims of a nuclear incident through a no-fault liability regime challenging liability to the operator'."[84] These two clauses, among several other deviations from the international Convention on Supplementary Compensation for Nuclear Damage (CSC), have had the chilling effect of dissuading private companies—especially foreign entities—from participating in India's nuclear power sector.[85]

The convoluted history of the passage of India's CLNDA is less relevant here. What is pertinent is that it has undermined what was meant to be the liberating effect of the U.S.-India Civil Nuclear Accord, namely, the entry of private, especially international, players into the Indian nuclear power program. Absent the protections offered by the international CSC—which substituted the lengthy process of legally proving supplier liability with a system of speedily compensating nuclear accident victims by enabling the operators of nuclear plants to draw on national insurance funds supplemented by an international pool—major private entities will shy away from the Indian nuclear energy sector.[86]

The deleterious consequences of the CLNDA's passage in 2010 were, in fact, felt immediately during the construction of the Kakrapar-3 reactor as Indian private companies resiled from providing components because of the fears about liability created by the law. The problem was not resolved until NPCIL indemnified its domestic suppliers through contract agreements, which in effect acknowledged that since NPCIL was the designer and supplier of the specifications governing the components involved, Indian vendors of these products would not be held liable in the event of an accident. [87]

The damage caused by the CLNDA still hangs over India's nuclear industry: it has deterred the foreign entry that would effectively leaven India's technology base, and it has subverted New Delhi's hope that foreign companies would manufacture nuclear systems and components in India for export abroad Obviously, other deterrents exist as well: the perpetual fears about New Delhi's policy inconsistency; the long delays in securing end-user assurances from the DAE regarding nonproliferation; the interminable delays in NPCIL's procurement process (just like in other Indian government acquisition activities); and the absence of intellectual property protection (because Indian law does not yet permit patents in the nuclear energy arena), have all taken their toll. But towering above these many impediments is the fear of burdensome liability that the CLNDA introduced, which will persist to India's disadvantage until it is forthrightly amended.

In the ramp up to India's 2024 elections, many of India's international partners—including countries that have had an active interest in entering its nuclear power sector, such as France, Japan, the United States, and South Korea—had hoped that Modi's third term would produce an early amendment of the CLNDA to rectify its impediments. U.S. policymakers engaged in many conversations with their Indian counterparts toward this end. Yet today, with Modi's diminished majority in parliament, the prospects for any decisive legislative relief are uncertain.[88] The Prime Minister's ruling coalition certainly has the votes required to amend the liability law if it were to pursue this option. But attempting to amend the law would likely provoke a bruising fight in the legislature, and, although its success is ultimately guaranteed, it could take a toll on the government's political fortunes. It is in fact very likely that the currently reinvigorated opposition would rake up all the ghosts of previous industrial accidents, and use the very arguments that Modi's party deployed when previously out of power to disfigure the original bill, to hinder any easy revision of the law this time around.

Although this is one instance, among many, when unity between government and opposition is demanded by India's national interests, it is unlikely to be forthcoming in part because the polarization across the political divide appears to have foreclosed the possibility of any constructive engagement.[89] For all practical purposes, therefore, a speedy amendment of the CLNDA may lie beyond reach, despite the entreaties of many of India's international partners including the United States. Consequently, its deleterious impact on India's nuclear power ambitions notwithstanding, the CLNDA may never see revision during Modi's third term.[90]

This is an eventuality that New Delhi's foreign partners will have to reckon with, however uncomfortably. To its credit, U.S. President Joe Biden's administration had intensified its efforts in recent years to persuade India to correct the impediments in its nuclear liability law because all the previous workarounds attempted by the Indian government had failed to yield the desired result. Neither the promise of a Government of India-funded insurance pool, nor the extra-legal assurances ginned up by India's Ministry of External Affairs in the form of officially articulated questions-and-answers for the record, nor the setting up of working groups between Indian and foreign officials to devise placatory solutions, nor the negotiation of comfort letters aimed at assuaging foreign industry have thus far resolved the conundrums posed by India's liability law. The latest suggestion proffered by Indian government officials—creating joint ventures between foreign nuclear suppliers and Indian public sector companies holding majority stakes—is unlikely to persuade Western firms that such arrangements would limit their liability risks (or serve their commercial interests) either.

On the face of it, therefore, there is plenty of room for pessimism about the prospects of change in India's legal regime—with unfortunate consequences for India's plans to expand the role of nuclear power in its energy mix. There is, however, one possibility that deserves further exploration: the direct indemnification of foreign suppliers, as NPCIL has already done with both domestic vendors and with Russia. For reasons that are inexplicable, NPCIL seems reluctant to universalize this solution, despite the payoffs it has produced in nuclear cooperation with Moscow.

The nuclear cooperation agreement signed between the Indian government and the Russian Federation in December 2008 for the construction of four more VVER-1000 reactors (units 3–6) offered Moscow full immunity on issues relating to liability through a contractual vehicle of the kind that has never been offered to any other international supplier. Article 13 of the agreement codifies this protection clearly:

> 13.1. The Indian Side and its authorized organization at any time and at all stages of the construction and operation of the NPP [Nuclear Power Plant] power units to be constructed under the present Agreement shall be the Operator of power units of the NPP at Kudankulam Site and be fully responsible for any damage both within and outside the territory of the Republic of India caused to any person and property as a result of a nuclear incident occurring at NPP and also in relation with a nuclear incident during the transportation, handling or storage outside the NPPs of nuclear fuel and any contaminated materials or any part of NPP equipment both within and outside the territory of the Republic of India.
>
> 13.2. Nuclear liability due to nuclear incident occurring when handling and transporting the fuel shall be transferred from the authorized Russian organization to the authorized Indian organization after physical handover of the fuel at the place of delivery.[91]

An indemnification of this kind is entirely consistent with the CLNDA because while the act empowers the Indian operator to seek remedies from its nuclear suppliers in case of an accident, it does not enjoin the operator to do so. Consequently, the operator can eschew exercising its right of recourse voluntarily as the Government of India has done on behalf of DAE/NPCIL in its agreement with Russia—and there is no reason why the Indian state cannot do likewise in all other agreements that may be negotiated with other foreign partners, especially France and the United States, given their desire to speedily enter the Indian nuclear sector.

To be sure, eliminating the impediments in the CLNDA through parliamentary amendment would be the first-best option for India and its international partners as New Delhi seeks to expand nuclear power production through the participation of private domestic and foreign entities in the Indian market. But if this alternative is unattractive for political reasons currently, immunizing private suppliers through negotiated contracts remains the next best alternative. It eliminates all the uncertainties associated with the more unwieldy solutions proposed by the Indian government thus far and would be acceptable to international suppliers just as it has been to private Indian and Russian state entities that are involved in the Indian nuclear power program.

All of India's international partners, of which France and the United States are the most prominent right now, therefore ought to insist on the incorporation of clauses similar to Article 13 in the Indo-Russia contract into their own nuclear cooperation agreements with India. It is, in fact, exceptionally perverse that the United States, which bore the lion's share of the burdens of legitimizing India's standing within the global nonproliferation regime, has to suffer the endless gyrations of working around the problems caused by the CLNDA when Russia has benefited from a simple solution that has permitted it to reap all of the commercial advantages.[92]

Resolving the problems caused to the foreign suppliers of nuclear reactors by absolving them of liability through a contractual solution works only if the construction of these plants are turnkey projects—as is the case where the Kudankulam nuclear power complex is concerned. If India hopes, as it should, that private companies (both Indian and foreign) in the future will not only construct nuclear reactors but actually operate them as purveyors of power to the Indian grid, then, New Delhi will have no choice but to fully fund the national insurance pool to cover the operators' liabilities in case of any accident.

India has not done so yet, even though it should do this because NPCIL's ability to compensate any victims of an accident arising from the nuclear power plants it operates would derive from its ability to tap into a fully funded national insurance pool.[93] This is obviously a less pressing constraint for NPCIL immediately because, as a government entity, it would be able to tap into sovereign resources in the event of an accident. But as India contemplates reforms in its nuclear sector to hopefully permit private nuclear power plant operators to function in the Indian market, having a fully funded national nuclear insurance pool, as required both by the CLNDA and the CSC, would be imperative.

In the absence of a legislative or a contractual rectification of the CLDNA's infirmities, fully funding the national nuclear insurance pool, however, cannot be offered by the Indian government as a substitute for including Article 13-like clauses in the nuclear cooperation agreements offered to Western nuclear suppliers. The Modi government might be tempted to offer such an insipid palliative. But proffering even a fully funded national nuclear insurance pool (or increasing its cap beyond current limits) will not eliminate foreign private sector concerns about the problems inherent in India's current liability law—and India's foreign government partners should resist accepting such a delusive solution if it is proposed by New Delhi.

Given the circumstances and the stakes involved, Modi—who has always and with justification prided himself on being a bold and decisive leader—should simply cut the Gordian knot of India's nuclear liability mess by either cleanly amending the CLNDA or reproducing the immunity assurance contained in the agreement with Russia in all other nuclear cooperation accords negotiated with other Western suppliers. After fifteen-odd years of recriminations about India's liability regime, the prime minister's laudable ambition to increase the share of nuclear power in India's energy basket demands no less.

Conclusion: A Long but Hopeful Road Ahead?

Close to seventy years after Homi Bhabha's now-famous three-stage plan was formally adopted by the Indian government as the template for developing nuclear power in India, the stage may finally be set for realizing something like a simulacrum of his vision. Clearly, technology and economics have conspired to undermine his "magnificent obsessions" of exploiting thorium to ensure India's energy independence over the long term.[94] But even as India's nuclear scientists and engineers continue to explore the possibilities of a thorium-driven nuclear fuel cycle, New Delhi has been gifted the opportunity of expanding its nuclear power program through new access to both the world's plentiful, low-cost, supply of natural uranium—which matches the economically extractable reserves of thorium globally—and to low-enriched uranium in any quantity India desires, not to mention being able to procure advanced nuclear reactor technology from various international suppliers. All these developments have potentially given India's domestic nuclear program a new lease on life.

Consequently, although Bhabha's three-stage plan is far from fruition, India today can do just as well without it, at least as far as producing nuclear power is concerned. This implies that energy does not need to become a constraint on India's ability to meet its economic development and climate mitigation goals. Transforming energy production from an impediment to an opportunity, however, will require New Delhi to persist with the goal of developing deep and more efficient markets across the Indian economy as a whole.

An important component of this effort will be reforming India's nuclear energy sector to permit private enterprise, both domestic and foreign, to play the widest possible role in all activities across the entire civilian nuclear cycle. It is amply clear by now that for all of the DAE's successes over the past few decades, India's nuclear renaissance cannot be engineered by its government and its public enterprises alone. Nor can the Indian private sector deliver by itself, or even in combination with the Indian state. Reaching India's energy production targets without expanding its carbon footprint will require significant foreign participation in the nuclear industry. Enabling this outcome requires reforms of the kind advocated in this paper.

Obviously, pursuing reforms pertaining to expanded access to the Indian market by itself will not guarantee private sector entry into the nuclear arena: such participation will depend equally on other factors such as the availability of technology, the price of capital, the competence of the interested entities, and the character of the liability involved. But the possibilities of what private participation in the Indian nuclear sector might produce cannot be tested without pursuing the three big transformations outlined here, ideas that must be reviewed and developed more systematically if they are to be successfully implemented.

Even at their best, however, these transformations—if realized—will constitute only necessary and not sufficient conditions for the expansion of nuclear power in India. A critical challenge that must be overcome is financing, especially on the scale required to underwrite the enlargement of nuclear energy envisaged by the IIM study cited earlier. India's development status does not easily qualify it for concessional loans from international lending institutions. But Moscow has provided New Delhi with big breaks on this count: the Russian state has financed the Indian purchase of its reactors at low interest rates, offering long repayment schedules, and most strikingly committing to accept reimbursement "from one year after the start of power generation."[95] India thus begins to pay back its Russian reactor construction loans only after these power plants are fully completed and are beginning to earn revenues by selling their electricity on the national grid.

It is unlikely that any private Western nuclear suppliers can match such terms. Only India's governmental partners in the West can offer favorable—even if not identical—financing packages.[96] But this makes it all the more important that India create a level playing field for Western companies by eliminating the burdens imposed by its liability regime if they are to benefit from their governments' export financing. For its part, New Delhi could also extend production linked incentives to Western nuclear suppliers to ease their entry into the Indian market. At the end of the day, however, whether India's nuclear power sector expands as dramatically as its votaries wish will depend fundamentally on the economics of producing nuclear electricity. India clearly *needs* nuclear power. But whether the solutions that satisfy this need are in fact viable—and cost effective across the economy writ large—cannot be tested unless the Modi government is willing to pursue the reforms necessary to increase the share of nuclear power within India's energy basket.

Despite the dismay currently swirling around his third term, Modi's reelection still offers the opportunity for restarting the process of structural reform that has effectively been stagnant in India since about 2020. Doubling down on reforms, to include restructuring India's nuclear estate, is now imperative if India is to realize the ambitions of becoming a developed country by 2047 and bringing its net carbon emissions down to zero by 2070. These are the goals that

Modi himself has promulgated: he owns them and now he must deliver. Where nuclear energy is concerned, he has offered tantalizing hopes of coming reform, but his initiatives here cannot be shy, piecemeal, or timid. Rather, the prime minister must articulate a comprehensive vision of change and focus on renovating the entire Indian nuclear enclave, even if the specific implementing initiatives are enacted in a careful and sequential manner over time.

It is unfortunate that India has had a long and checkered history of frequently pulling defeat from the jaws of victory. Today, the costs of a stillborn economic transformation are inordinately high, given the insistent clamor for satisfying unmet aspirations within India itself and the unfavorable alterations in India's external environment. Failing to complete the reforms that advance India's development—of which expanding nuclear energy production is only a part—will precipitate a fateful faltering when India, yet again, has economic, strategic, and geopolitical success in sight. But it need not happen, if Modi focuses on the right transformations that make India the best that it can be.

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Acknowledgments

The author is deeply grateful to Gopalan Balachandran, Gregory S. Jones, and Basant Sanghera for their detailed and most helpful comments on this paper and to Caroline Mallory and Annabel Richter for helping to bring it to publication.

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