

Designing for Optionality: Preserving the Nuclear-Fertiliser Integration Option in India's Reactor Programme

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Abstract

Three developments in 2026 frame the argument of this paper. On April 6, the Prototype Fast Breeder Reactor at Kalpakkam achieved first criticality. Three weeks earlier, missiles struck the Ras Laffan industrial complex in Qatar, and by late April India was contracting urea imports at close to twice the price prevailing in February. On June 26, the Department of Atomic Energy inaugurated a facility producing hydrogen from the copper-chlorine thermochemical cycle using process heat drawn from the Fast Breeder Test Reactor, the first such installation anywhere in the world. India's urea import dependence rests on the Haber-Bosch process, which requires a large and continuous supply of hydrogen, and that hydrogen is at present made from natural gas. Nuclear process heat offers a different route to that hydrogen, and India has now demonstrated the core of it at bench and pilot scale. This paper does not argue that India should build integrated nuclear-fertiliser complexes now. It argues something narrower. The greater part of India's planned nuclear capacity is still in the designing stage, and decisions being taken today about reactor design, site allocation, environmental clearance and the rules under the SHANTI Act, 2025 will determine whether integration remains available as a future choice or becomes practically foreclosed. This paper tries establishing six provisions that would keep the option open. Each is inexpensive to adopt now, and difficult or impossible to add once a reactor has been built and licensed.

Keywords: nuclear energy policy; fertiliser policy; nuclear process heat; energy security; urea subsidy; India

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1. Introduction

On the evening of April 6, 2026, the 500 MWe Prototype Fast Breeder Reactor (PFBR) at Kalpakkam achieved first criticality. Twenty-two years after construction began and sixteen years after the originally projected completion date, India became the second country after Russia to operate a commercial-scale fast breeder reactor (DD News 2026; Al Jazeera 2026a; International Panel on Fissile Materials 2026). The Department of Atomic Energy positioned the event as the bridge from Stage I uranium reactors towards the thorium-based third stage of the programme that has guided Indian nuclear policy since the 1950s (Department of Atomic Energy 2026).

Three weeks earlier, on March 18, 2026, missiles struck the Ras Laffan Industrial City in Qatar, the world's largest liquefied natural gas (LNG) production facility and the source of a substantial fraction of India's LNG and urea imports (Al Jazeera 2026b; Argus Media 2026). On April 23, Indian Potash Limited contracted 2.5 million tonnes of urea at \$935 to \$959 per tonne, close to twice the price prevailing in February of the same year (Business Today 2026a; The Tribune 2026).

On June 26, 2026, the Department of Atomic Energy inaugurated a hydrogen production facility at the Indira Gandhi Centre for Atomic Research (IGCAR) at Kalpakkam, using the copper-chlorine (Cu-Cl) thermochemical cycle driven by process heat from the Fast Breeder Test Reactor (FBTR). The Department describes it as the first facility of its kind anywhere, and as a technology demonstrator intended to generate operating experience for eventual scale-up (Press Information Bureau 2026).

These three developments describe the situation Indian policy now must work within. India's urea import dependence is not fundamentally a dependence on urea. It is a dependence on natural gas, which supplies the hydrogen that becomes ammonia and then urea. A hydrogen route that does not begin with methane would change the underlying position rather than manage it, and India has now demonstrated one such route.

Less follows from that than might appear. The FBTR facility is a demonstrator on a small test reactor. It establishes that nuclear process heat can drive the Cu-Cl cycle (The technical details of the Cu-Cl cycle do not affect the argument of this paper). It does not establish that hydrogen produced this way is economic, that it competes with hydrogen produced by electrolysis from renewable power, or that any particular reactor design should be built for the purpose. Those questions are open, and several of the technologies involved are first of a kind, which means the answers will not be known for some years.

The argument of this paper does not depend on those answers. India is at present designing, siting and clearing the greater part of the nuclear capacity it intends to build over the next two decades. Reactor designs are being finalised. Sites are being allocated under the Nuclear Energy Mission. Rules are being drafted under the SHANTI Act, 2025.

Each of these decisions either preserves or removes the possibility of coupling a reactor to a fertiliser plant later. A reactor built without a thermal offtake point, on a site with no adjacent land, under a

clearance that does not contemplate a chemical facility, cannot readily be integrated afterwards. The cost of retaining that possibility now is small. Once the civil work is done and the mechanical systems have been designed, ordered and installed, adding certain functionalities at a later date could be very expensive, very difficult, or impossible.

This is an argument about preserving an option under uncertainty rather than about making a commitment. It asks the Indian state to decide, at a point where the decision is nearly free, that a future government should be able to choose integration if the economics and the technology support it. It does not ask that government to be committed to that choice in advance.

The paper proceeds as follows. Section 2 sets out the present state of Indian nuclear and fertiliser policy, including the green ammonia procurement now under way, which is the most serious alternative route to the same objective. Section 3 explains why integration has to be designed in rather than added later, and states plainly what remains unknown. Section 4 sets out the six provisions. Section 5 addresses risks and limitations, including the safety questions raised by siting hydrogen and ammonia facilities near a reactor, and the possibility that the option is never exercised. Section 6 concludes.

2. The Present State of Indian Nuclear and Fertiliser Policy

2.1 The Nuclear Programme

The Nuclear Power Corporation of India Limited (NPCIL) operates 24 reactor units with a combined installed capacity of 8,780 MWe (Nuclear Power Corporation of India Limited 2026). The substantial majority are Stage I pressurised heavy water reactors, at Tarapur, Rawatbhata, Kalpakkam, Narora, Kakrapar and Kaiga, alongside two pressurised water reactors at Kudankulam. Rajasthan Atomic Power Station Unit 7, a 700 MWe pressurised heavy water reactor, entered commercial operation on April 15, 2025. In the first four months of the 2026-27 financial year, the fleet recorded a capacity factor of 90%, and an availability factor of 95% (Nuclear Power Corporation of India Limited 2026). Nuclear power contributes roughly three per cent of India's electricity generation.

The PFBR that achieved criticality in April 2026 sits outside this fleet. It is operated by Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI) rather than NPCIL. It uses uranium-plutonium mixed oxide fuel reprocessed from Stage I reactors and is designed to breed further fissile material in a blanket, initially of uranium-238 and later of thorium-232. It is a pool-type sodium-cooled design with a sodium outlet temperature in the region of 550 °C (Department of Atomic Energy 2026; International Panel on Fissile Materials 2026).

The Union Budget of February 2025 announced a Nuclear Energy Mission with an outlay of Rs 20,000 crore, directed at research and development of small modular reactors, with a target of at least five indigenously designed units operational by 2033 (Press Information Bureau 2025). The Department of Atomic Energy is developing three designs: the 220 MWe Bharat Small Modular Reactor, a 55 MWe unit, and a 5 MWth high-temperature gas-cooled reactor intended exclusively for

hydrogen production (Business Standard 2025). The broader policy target is 100 GW of nuclear capacity by 2047, against 8.78 GW today (Observer Research Foundation 2026).

The legislative framework changed in December 2025. The Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India (SHANTI) Bill was tabled in the Lok Sabha on December 15, passed by that house on December 17 and by the Rajya Sabha on December 18, and received presidential assent on December 20, 2025 (World Nuclear News 2025). The SHANTI Act, 2025 repeals the Atomic Energy Act, 1962 and the Civil Liability for Nuclear Damage Act, 2010. It permits Indian companies and joint ventures to build, own, operate and decommission nuclear power plants under licence from the central government, establishes a dual-permit structure combining a government licence with a safety authorization from the Atomic Energy Regulatory Board, and gives the AERB statutory standing for the first time (Takshashila Institution 2026). Enrichment, heavy water production and spent fuel management beyond on-site storage remain with the Department of Atomic Energy. Notably for the purposes of this paper, the Act covers non-power applications of nuclear energy and ionizing radiation, not only power generation.

The relevant feature of all this, for my argument, is how little of it is fixed. Roughly 92% of the capacity India intends to have in 2047 does not exist yet. Most of it has not been designed. Much of it has not been sited. The rules under the SHANTI Act are still being written.

2.2 The Fertiliser Position

India's urea import dependence has been widening. Imports between April and November 2025 reached 7.17 million tonnes against 3.26 million tonnes in the corresponding period of the previous year, driven by declining domestic production and rising consumption (Fertiliser Association of India 2026; Press Trust of India 2025). The 2025-26 Union Budget allocated Rs 1.68 lakh crore for fertiliser subsidies, of which Rs 1.19 lakh crore was for urea alone (Department of Fertilizers 2025). Following the price shock of April 2026, the revised estimate for the urea component is expected to approach Rs 1.42 lakh crore (BusinessToday 2026b).

The structural dependence runs through natural gas, which supplies the hydrogen for ammonia synthesis through steam methane reforming. Gulf and Russian sources supply the bulk of both imported gas and imported urea. Domestic producers, even when supplied at concessional gas prices under the priority allocation regime announced in March 2026, cannot match the landed cost of Gulf urea – which is produced from gas that is close to free at the wellhead (Ministry of Finance 2024; BusinessToday 2026b).

2.3 The Green Ammonia Route

Any argument for nuclear-derived hydrogen in fertiliser production has to take account of the route India is already taking. Under the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme of the National Green Hydrogen Mission, the Solar Energy Corporation of India (SECI) ran a competitive reverse auction for green ammonia supply to fertiliser plants. The

discovered prices ranged from Rs 49.75 to Rs 64.74 per kilogram, against a global benchmark of roughly Rs 110 per kilogram. In March 2026, ACME Cleantech, NTPC Renewable Energy, Jakson Green and Oriana Power signed ten-year binding supply agreements covering 724,000 tonnes a year across 13 fertiliser units (Business Standard 2026).

This is a real programme with discovered prices and signed offtake agreements, and it is further advanced than anything nuclear can offer in this decade. The comparison is taken up in Section 5. For the present, two things about it are worth registering. The volumes are small relative to the problem: India consumes between 17 and 19 million tonnes of ammonia annually, so the first SIGHT tranche covers around 4% of consumption. And the constraints on scaling it are physical rather than commercial, which is the point at which nuclear cogeneration becomes relevant rather than redundant.

2.4 The Anomaly

India is expanding its nuclear capacity while its fertiliser import dependence widens. In its present form the first will do nothing about the second. Additional nuclear capacity will produce electricity, displace some fossil generation and contribute to climate goals. None of that touches the gas-feedstock dependence at the centre of the urea production chain. Connecting the two requires a deliberate decision, and the window in which that decision can be taken cheaply is the design stage.

3. Why Integration Has to Be Designed Rather Than Added

3.1 The Thermodynamic Case and its Limits

The conventional route from nuclear energy to fertiliser runs through the grid. A reactor produces electricity; which is then sold; a fertiliser plant elsewhere buys electricity at industrial tariffs, uses it to electrolyse water, combines the resulting hydrogen with nitrogen in a Haber-Bosch reactor, and reacts the ammonia with carbon dioxide to make urea. Each conversion loses energy. Heat to electricity runs at roughly 40% for a fast reactor. Electricity to hydrogen by low-temperature electrolysis runs at 65-75%. The compounded efficiency from reactor heat to hydrogen is around 28%.

Thermochemical cycles use reactor heat directly. Published efficiency estimates for the Cu-Cl cycle vary widely, from around 32% to nearly 59% depending on configuration and assumptions (Rosen et al. 2012; Bhabha Atomic Research Centre n.d.). Taking a mid-range figure of about 43%, the thermochemical route consumes roughly a third less reactor thermal output for the same quantity of hydrogen than the electrical route does.

The limit of this claim is easily overstated. It does not mean that using reactor heat for hydrogen is close to free in terms of foregone electricity. The Cu-Cl cycle requires heat at around 530 °C, which is at the top of the temperature range a sodium-cooled fast reactor delivers. This is not heat that would otherwise be rejected to the condenser. It has to be taken from the secondary loop ahead of the steam generator, and every thermal megawatt taken is a thermal megawatt not raising steam. The correct

comparison is between thermochemical and electrolytic routes to the same hydrogen, and on that comparison the thermochemical route sacrifices less – but by no means little – generation.

The terminology matters here as well. What is under discussion is cogeneration, or in the International Atomic Energy Agency's (IAEA) usage a non-electric application, not the diversion of heat from electricity generation. Roughly 67 reactors worldwide, about 15% of the global fleet, already supply district heating, desalination or industrial process heat alongside electricity (International Atomic Energy Agency n.d.). The Nuclear Energy Agency has published a standard method for costing this, in which the cost of nuclear heat is treated as the sum of heat-specific capital and operating costs and the opportunity cost of electricity not generated (Nuclear Energy Agency 2022). That method is available to eventually do the sums for an Indian project.

3.2 What India has Already Demonstrated

The Bhabha Atomic Research Centre (BARC) has developed and demonstrated two thermochemical hydrogen processes: the copper-chlorine cycle and the iodine-sulphur (I-S) cycle (Bhabha Atomic Research Centre n.d.). Both were confirmed as demonstrated technologies in a statement to Parliament by the Minister of State in July 2025 (Business Standard 2025).

Two facilities matter. The first is the Cu-Cl installation inaugurated at IGCAR Kalpakkam in June 2026, drawing process heat from the FBTR (Press Information Bureau 2026). The second is a demonstration plant for the iodine-sulphur process, on which construction began in March 2025, built by the Heavy Water Board in collaboration with BARC and located at the Heavy Water Board's facilities within the premises of Rashtriya Chemicals and Fertilizers Limited in Mumbai (Deccan Herald 2025).

The latter deserves more attention than it has received. India has already placed a nuclear-establishment thermochemical hydrogen plant inside a fertiliser company's site. The heat source in that case is not a reactor, but the physical and institutional arrangement is precisely the one this paper is concerned with. It suggests that the co-location question is not novel to the Indian system, and that the barriers to it are more procedural than conceptual.

A third element is planned rather than built. The 5 MWth high-temperature gas-cooled reactor under development is intended exclusively for hydrogen production, coupled to a suitable thermochemical process (Business Standard 2025; Observer Research Foundation 2026). Which process, and at what scale, has not been settled.

3.3 What is not Known

Several things that a policy proposal would normally want to rest on are simply not available.

No reactor design has been selected for integrated operation. India's own establishment has not converged on a third-stage design, and the reactor classes capable of supplying heat at the temperatures thermochemical cycles need are limited: fast reactors and high-temperature gas-cooled reactors.

Pressurised heavy water reactors, which make up most of the operating fleet, run below 350 °C at outlet and cannot drive these cycles directly.

Neither has the process been selected. Cu-Cl and I-S have both been demonstrated at bench and pilot scale in India, and there is no basis yet for preferring one. Published cost estimates for Cu-Cl hydrogen span from under \$2 to over \$15 per kilogram, and for I-S from around \$2 to nearly \$12, which is a range too wide to support any policy conclusion (Rosen et al. 2012). These are engineering-economic models rather than plant data, because no commercial-scale facility of either kind exists anywhere.

Nor is the scale of the eventual coupling established. As a rough indication of the order of magnitude involved: producing a tonne of urea requires roughly 100 kilograms of hydrogen, so a million tonnes a year would need about 100,000 tonnes of hydrogen, which at 43% thermal efficiency implies something in the region of 900 MWt of continuous thermal input. A PFBR-class reactor produces around 1,250 MWt. The point of the calculation is only that meaningful urea output would consume a large fraction of a reactor's thermal capacity rather than a marginal slice of it, and that any claim to the contrary should be treated sceptically. It is not an engineering estimate, and should not be read as one.

3.4 Why this Argues for Provisioning Rather than Waiting

The natural response to that list of unknowns is to wait until they are resolved. That would be right if the relevant decisions could be deferred. They cannot.

Reactor designs are being finalised now. A design that includes a defined thermal offtake point on the secondary loop can be coupled to a chemical plant later. One that does not cannot be modified without reopening the design, the safety case and the license, on a plant that by then is operating. Sites are being allocated now. A site with reserved adjacent land can host a chemical facility later. One hemmed in by acquisition that stopped at the reactor boundary cannot, and acquiring land next to an operating nuclear plant, years after commissioning, is among the more difficult things to attempt in Indian infrastructure. Environmental clearances are being granted now, and a clearance that does not contemplate a chemical facility will require a fresh assessment and public hearing if one is proposed later. The rules under the SHANTI Act are being drafted now, and rules that provide no route to a combined nuclear-chemical license will have to be amended before such a facility can be authorised.

In each case the asymmetry is the same. Including the provision at design stage costs very little. Adding it afterwards costs a great deal, and in some cases cannot be done at all. That asymmetry is the whole of the argument, and it holds whether or not integration eventually turns out to be economic.

4. Six Provisions

What follows are the provisions I propose. They are deliberately modest. None of them commits India to building an integrated complex, and none requires a judgement about which reactor or which process is best. The intent here is that if a future government decides to integrate, it will be able to do so.

4.1 Provision One: thermal offtake capability

Reactor designs now being finalised, in the fast reactor and high-temperature classes, should retain a defined heat offtake point on the secondary circuit, or at minimum reserve the space, penetrations and structural allowance for one to be added. The distinction matters. A full offtake system fitted from the outset costs more than a reserved provision, and for reactors whose eventual coupling is speculative the reserved provision is the sensible option. What matters is that the possibility should not be ignored or removed by default. If a design team concludes that an offtake provision is not worth making, that conclusion should be reached deliberately and the reasoning recorded, so that it can be revisited when the question of integration becomes live.

This consideration should not extend to pressurised heavy water reactors, whose outlet temperatures cannot support thermochemical cycles. It is a provision for a subset of the fleet, and it should be applied as such.

4.2 Provision Two: site footprint and land reservation

Site allocation should reserve adjacent land within or beside the plant boundary sufficient for a future chemical facility. This is the least expensive provision on the list and probably the most consequential, because land is the constraint that is hardest to relax retrospectively. Reserved land carries a holding cost and no more. Land that has to be acquired later - adjacent to an operating reactor - involves an acquisition process, a public consultation, and a political negotiation that may simply fail.

Siting criteria should also take account of proximity to biogenic carbon dioxide sources, since urea synthesis requires carbon dioxide that a nuclear route does not supply as a by-product, and to the agricultural distribution network. These are preferences rather than requirements, and they should be weighed alongside the seismic, hydrological and demographic criteria that govern nuclear siting and should continue to take precedence.

Land is the one provision that the central government cannot deliver on its own. Land acquisition, water allocation and the local political management of large industrial projects sit with the states, and the record of Indian infrastructure suggests that state cooperation determines outcomes more often than central intent does. Tamil Nadu, Maharashtra, Gujarat, Karnataka and Rajasthan host the existing nuclear infrastructure and are the natural candidates (Nuclear Power Corporation of India

Limited 2026). Each has some prior interest in industrial cluster development that a reserved-land arrangement could attach to.

What a state gets from reserving land for a facility that may never be built is not obvious, and the proposal should be honest about that. A reservation with no compensating benefit will be resisted, and reasonably so. The more workable approach is to treat the reservation as part of the existing site negotiation rather than as a separate ask, and to establish at that point what a state would receive if the option were later exercised. That might be a share of the foreign exchange saved on displaced urea imports, or a call on output for distribution within the state. Settling the principle early costs nothing; leaving it until a state is asked to release land next to an operating reactor is how such requests fail.

4.3 Provision Three: clearance scope

Environmental clearance and site approval for reactors in the relevant classes should be sought on a basis that contemplates a future co-located chemical facility, even where none is proposed. The cost of doing so at the outset is the cost of a somewhat broader assessment. The cost of not doing so is a fresh environmental impact assessment and public hearing at the point when integration is proposed, on a site where a nuclear plant is already operating and public attention is correspondingly higher.

4.4 Provision Four: safety case scope

The Atomic Energy Regulatory Board's siting and hazard analysis for these reactors should consider hydrogen and ammonia inventories at the design stage, whether or not a chemical facility is being built. Introducing a new hazard into an approved safety case afterwards is materially harder than including it from the beginning, because it reopens questions that were settled on the assumption that the hazard was absent. The substantive safety questions are set out in Section 5; the point here is procedural. The analysis should be done while it is cheap to do.

4.5 Provision Five: regulatory and standards pathway

The rules under the SHANTI Act, 2025 are being drafted. They should provide a route by which a facility that is simultaneously a nuclear installation and a chemical plant can be licensed, rather than requiring two unconnected approval processes with no defined relationship between them. The Act's dual-permit structure, combining a central government licence with an AERB safety authorization, gives a natural framework for this (Takshashila Institution 2026), and the Act's coverage of non-power applications suggests the drafters have already contemplated uses beyond generation.

Standards require a similar layering. The Bureau of Indian Standards and the Fertilizer Control Order regime cover the fertiliser side domestically, and AERB covers the nuclear side. Neither addresses the interface. No settled national or international standard governs co-located nuclear-chemical complexes, and the relevant international material, principally IAEA guidance on non-electric applications (International Atomic Energy Agency n.d.) and ISO standards for hydrogen and

ammonia handling, would have to be adapted rather than adopted as-is. That adaptation work should begin now, because standards development is slow, and the absence of standards is a common reason for projects to stall.

4.6 Provision Six: ownership and operating model

The SHANTI Act permits Indian companies and joint ventures to build, own and operate nuclear power plants. It does not answer who would own and operate a facility that is both a reactor and a fertiliser plant. The question is not academic. A nuclear licensee and a fertiliser producer have different regulators, different competences, different capital structures and different commercial logics, and a joint facility needs a clear answer on where responsibility sits, particularly for safety.

Several arrangements are possible. The reactor could be licensed to a nuclear operator, public or private, which sells heat and electricity to a separately owned fertiliser plant under long-term contract. A joint venture could hold both. A fertiliser producer could contract for the nuclear operation. Each has different implications for liability, for tariff regulation and for who bears the risk of the reactor being unavailable. I do not propose to settle the question here. I propose that the rules being drafted should not inadvertently exclude the workable arrangements, which is what will happen if the question is never asked.

4.7 The trigger

I do not propose a calendar date. A fixed date would be arbitrary, and the whole force of the argument is that the relevant moment is defined by the decision rather than by the year. The trigger should be the design decision itself: any reactor in the fast or high-temperature classes that has not yet reached design freeze, any site not yet allocated, any clearance not yet sought, and the SHANTI rules not yet notified.

In practice this covers most of what India intends to build.

4.8 What the provisions cost

The provisions are cheap because none of them builds anything. A reserved offtake point is a design allowance. Reserved land is a holding cost. A broader clearance is a somewhat longer assessment. A wider safety analysis is analytical work. A licensing pathway and a standards programme are administrative effort. Taken together, they are a small fraction of the cost of a reactor, and a very small fraction of the Rs 20,000 crore Nuclear Energy Mission outlay (Press Information Bureau 2025).

Against that, the cost of foreclosure is the cost of the alternative. If integration is later judged worthwhile and the provisions were not made, the choice will be between retrofitting an operating reactor, which may not be feasible, and building a new one for the purpose, at full capital cost, on a new site with a new clearance. Neither of those is a small number. It is not necessary to know whether

integration will prove economic in order to see that the ratio between these two costs justifies the provisions.

5. Risks, Limitations and What This Does Not Address

5.1 Safety risks of co-location

Placing hydrogen and ammonia facilities near a nuclear reactor introduces hazards that neither industry faces alone, and this is the most substantive objection to the proposal.

Hydrogen is flammable across a wide range of concentrations in air, has very low ignition energy, and burns with a nearly invisible flame. Its behaviour in nuclear settings is well understood for unhappy reasons: hydrogen generated by fuel-cladding oxidation caused the explosions that destroyed the reactor buildings at Fukushima Daiichi in 2011. A deliberate hydrogen inventory adjacent to a reactor is a different situation, since hydrogen is contained by design rather than released by accident, but the consequence analysis draws on the same physics. Ammonia presents a different hazard, being toxic by inhalation and stored in quantity, with the risk being dispersion of a toxic cloud rather than blast.

The concerns for a co-located facility are of three kinds. A detonation or deflagration in the chemical plant could damage reactor structures or safety systems or produce a pressure wave affecting the control room. A toxic release could force evacuation of personnel whose presence is required to operate the reactor safely, creating a situation in which the chemical hazard degrades the nuclear response. And an emergency at one facility could complicate the response at the other, if emergency plans, command arrangements or evacuation routes were designed independently.

The established mitigations are separation distance, blast-resistant design of reactor structures facing the chemical plant, inventory limits, siting the chemical facility with regard to prevailing wind direction relative to the control room and main access routes, and a single integrated emergency plan rather than two. Separation distance is the central variable, and it is also the one that has to be settled early, because it determines the site footprint and therefore Provision two. The IAEA has addressed hydrogen production near nuclear plants within its work on non-electric applications (International Atomic Energy Agency n.d.), and that material would be the starting point for an Indian analysis.

These are design questions rather than residual risks to be noted at the end. The reason for Provision four is precisely that they are cheap to answer while a reactor is on paper and expensive to answer once it is operating.

5.2 The option may never be exercised

The provisions might be adopted and integration never pursued, because renewable hydrogen turns out cheaper, because thermochemical cycles do not scale, or because reactor construction slips far enough that the question becomes moot. In that case the money spent on the provisions is wasted.

I accept this, and it is the correct way to think about the proposal. What is being bought is an option, and options sometimes expire unexercised. The case rests on the premium being small relative to the value of the option, not on the option being certain to pay. Anyone who believes integration will never be worthwhile under any future conditions should reject this proposal, and the argument between us would be about that belief rather than about the provisions.

5.3 The comparison with renewable hydrogen

The most serious challenge to any nuclear-fertiliser proposal is that renewable hydrogen already does the job. The SECI auction discovered green ammonia prices between Rs 49.75 and Rs 64.74 per kilogram, well below global benchmarks, with ten-year agreements signed and volumes allocated across 13 fertiliser plants (Business Standard 2026). Nuclear cannot offer anything comparable in this decade or probably the next.

I do not dispute this and I do not propose to argue that nuclear hydrogen will be cheaper. The published cost ranges for thermochemical hydrogen are too wide to support such a claim, and they are model outputs rather than plant data, whereas the SECI figures are discovered prices from a competitive auction. Comparing the two directly would be comparing a projection with a transaction.

The relationship is better understood as complementary. India consumes 17 to 19 million tonnes of ammonia a year, and the first SIGHT tranche addresses roughly 4% of that. Scaling green ammonia by an order of magnitude runs into two physical constraints. The first is capacity factor. Over a year, Indian solar plants deliver only about 20 to 25% of the energy they would produce if they ran at full output continuously. Ammonia synthesis cannot easily follow a supply that varies on that scale: the synthesis loop must be held at steady temperature and pressure, the catalyst suffers from repeated thermal cycling, and a restart takes hours. A renewable route therefore needs either a substantially larger solar build paired with storage, or a steady supply of green power from elsewhere. The second is land, which competes directly with agriculture in exactly the regions where fertiliser demand is highest.

Neither constraint is decisive at 4% of consumption; both become significant at 40%. The relevant question is therefore not whether nuclear beats renewables for the first tranche, which it plainly does not, but whether India will want a second source when the cheap and easily developed renewable resource has been committed. That is a question for the 2040s, which is when the reactors being designed today will be operating.

5.4 Timing

Stage III reactors are not operational, the first small modular reactors are targeted for 2033, and the 100 GW figure is for 2047 (Press Information Bureau 2025; Observer Research Foundation 2026). The urea import problem is immediate. It is fair to object that a proposal operating on a twenty-year horizon does nothing about a present difficulty.

The objection is correct and I do not think it damages the proposal, because the proposal is not offered as a response to the immediate problem. Domestic gas allocation, the green ammonia procurement under SIGHT, and diversification of import sources are the near-term instruments and they are already in use. The provisions proposed here operate on the horizon at which reactor infrastructure operates, and that horizon is set by physics and construction schedules rather than by preference. What the timing does establish is urgency of a different kind: the decisions being preserved or foreclosed are being taken now, whatever the operating date turns out to be.

5.5 Cost overruns and delivery risk

The PFBR was completed at roughly Rs 8,181 crore against an original estimate of Rs 3,492 crore, sixteen years late (International Panel on Fissile Materials 2026). Cost overruns and schedule slippage in Indian nuclear construction are the norm rather than the exception, and there is no reason to expect a co-located chemical facility to improve matters.

The provisions proposed here are relatively insulated from this, because they do not involve construction. A design allowance, a land reservation and a broader clearance are not subject to the same delivery risk as a reactor. If the reactor is delayed, the provisions are delayed with it and nothing further is lost. This is a further argument for provisioning rather than building: it separates the cheap and reversible decisions from the expensive and irreversible ones and only asks for commitment on the former.

5.6 The carbon dioxide requirement

Urea synthesis requires carbon dioxide. Gas-based urea gets it free as a by-product of steam methane reforming. A nuclear route does not have this luxury. It would have to be sourced from fermentation at ethanol distilleries, from biomass gasification, or from captured industrial flue gas. This is a smaller part of the overall requirement and can be arranged in several ways, and it applies equally to the renewable hydrogen route, so it does not distinguish between the two. It is nonetheless a real logistical requirement, and it bears on siting. India's ethanol blending programme generates fermentation carbon dioxide at distilleries. This is largely vented at present, and provides the most plausible source, although I am not aware of a published assessment of the volumes involved or their geographic distribution relative to candidate reactor sites. I do not go any further into that assessment here.

5.7 Equity and distribution

An integrated complex would produce urea for distribution through the existing network and would therefore inherit rather than address the smallholder access and tenant farmer questions that affect the current fertiliser regime. Empirical work by Gordeev and Singh (2024) under the Structural Transformation and Economic Growth programme finds that fertiliser subsidies are weakly supply-side regressive while the public distribution system is demand-side progressive. That finding bears on

any proposal to shift public spending between the two. The proposal here does not require such a shift, and I take no position on the broader subsidy reform debate, but the distributional questions remain live and are not answered by changing where hydrogen comes from.

5.8 Concentration risk

A site combining a reactor, a hydrogen facility and an ammonia plant is a higher-value target than any of them alone, as the strikes on Ras Laffan and Mesaieed in March 2026 illustrated for the Gulf complexes (Al Jazeera 2026b; Argus Media 2026). This is a real consideration, though it applies in some measure to existing Indian nuclear sites, several of which already host multiple reactors. Geographic distribution across sites rather than concentration at one, and the protective arrangements that already apply to nuclear installations, are the available responses. It should also be noted that the present architecture carries its own concentration risk, located offshore and outside Indian control, which is what the April 2026 price shock demonstrated.

6. Conclusion

India is at an unusual and, in some respects, critical moment in its nuclear programme. It has just brought a fast breeder reactor to criticality, demonstrated thermochemical hydrogen production from nuclear heat for the first time anywhere, and passed legislation that reorganises the sector and opens it to private participation. It has also, in the same few months, contracted its largest ever urea import at close to twice the previous price. The connection between these facts is that urea dependence is gas dependence, and nuclear process heat offers a route to hydrogen that does not start with gas.

I have not argued that India should act on that connection now. Too much remains unsettled. No reactor design has been chosen for the purpose, no thermochemical process has been selected between the two that BARC has demonstrated, and the cost estimates in the published literature vary over a very wide range, plainly because no commercial plant exists anywhere against which they could be calibrated. A proposal to build integrated complexes today would ask the state to commit based on evidence that does not yet exist or exists only in fragments.

What I have argued is that the absence of that evidence is not a reason for inaction. A decision is being taken in either case, and it is better taken with the future possibility in view than by default. India is designing and siting the great majority of the nuclear capacity it intends to operate in 2047. Every one of those design and siting decisions either preserves the possibility of integration or removes it. Reactors will be designed with or without a thermal offtake point. Sites will be allocated with or without adjacent land. Clearances will be sought on a basis that contemplates a chemical facility or on one that does not. Rules will be drafted under the SHANTI Act that provide a route to a combined license or that do not. These decisions are being made now, by default if not deliberately; but the defaults here should not close the future doors.

The six provisions set out in Section 6 are intended to make the choice deliberate. They are a design allowance, a land reservation, a broader clearance, a wider safety analysis, a licensing pathway and an answer to the ownership question. None of them builds anything. None commits a future government to integration, and none requires a judgement about technologies that have not yet been proven. What they do is ensure that when the evidence is available, in the 2040s, a decision remains available too.

The alternative is not that India decides against integration. The alternative is that India does not decide at all and discovers in twenty years that the choice was made by omission in the design offices of the 2020s. That would be an expensive way to settle a question that could have been left open at almost no cost.

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