

Selective Strategic Autonomy in Critical Minerals and Devices: Thermoelectrics as a Probe Case for Viksit Bharat 2047

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Abstract

Viksit Bharat 2047 offers an opportunity to strengthen the materials and electronics capabilities underpinning India's digital, industrial, space, and strategic ambitions. This paper develops a framework for selective strategic autonomy in critical materials and devices, combining domestic capability in priority segments with diversified international partnerships for inputs India cannot supply competitively. Thermoelectrics, the solid-state conversion of heat into electricity and of electricity into cooling, without moving parts, provides a deliberately bounded probe case. Its compact mine-to-module value chain allows mineral governance, technology access, manufacturing, finance, qualification, and recovery to be examined together. The paper presents three scenarios for 2047 and identifies strategic autonomy with managed interdependence as the most practical pathway. It proposes a next-stage agenda building on the NCMM, ISM, PLI schemes, iDEX, and Centres of Excellence through stage-specific finance, technology partnerships, selective module manufacturing, domestic qualification, and circular recovery. By-product recovery, mine waste, end-of-life devices, and segregated pharmaceutical waste are identified as feedstocks requiring pilot-scale validation. It also recommends an early mission-mode programme for high-temperature materials, module reliability, and qualification for strategic and space applications. Its contribution is a practical mine-to-module roadmap for converting India's policy foundations and research strength into resilient capability in selected deep-tech segments.

Keywords: Viksit Bharat 2047; deep-tech policy; critical minerals; thermoelectrics; materials sovereignty; technology commercialisation

JEL Codes: O25; F52; Q38; L63

Publication Date: 26 October 2026

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1. Introduction

India's dependence on China for the processing of critical minerals, including tellurium, bismuth, antimony, germanium, gallium, and rare earth elements, creates a structural vulnerability that receives limited attention in mainstream discussions of Viksit Bharat 2047 (Ministry of Mines 2023; United States Geological Survey 2024). Although these discussions emphasise digital public infrastructure, services exports, and the demographic dividend (NITI Aayog 2025), they give comparatively little attention to the materials and electronics base on which these ambitions depend.

The scale of the challenge is considerable. Fifteen countries control more than 55% of the world's identified critical-mineral resources, and China processes 87% of global rare earth elements (VIF 2025). The World Bank estimates that production of graphite, lithium, and cobalt will need to rise by more than 450% from 2018 levels to meet energy-storage demand by 2050 (Hund et al. 2020). India is fully import dependent for ten critical minerals, and its reliance on China exceeds 80% for several others (Shetty 2024). China's December 2024 ban on exports of gallium, germanium, and antimony to the United States confirmed that mineral supply chains can be used as instruments of geoeconomic leverage (Global Trade Alert 2025; Stimson Center 2025).

India has established important institutional foundations through the National Critical Mineral Mission (NCMM), the India Semiconductor Mission (ISM), and the Production-Linked Incentive (PLI) schemes. The next phase should strengthen the links across the full chain that turns a mineral in the ground into a finished device and then recovers that device at the end of its life. One step in that chain, qualification, needs a word of explanation: it is the formal testing and certification that proves a device will perform reliably under the conditions of its intended use, and it is what allows a component to be accepted into an industrial, defence, or space system. This would convert complementary initiatives into a more integrated capability pathway.

This paper treats materials sovereignty as selective strategic autonomy rather than autarky. By 'selective strategic autonomy', we mean building the capacity to act in priority segments through domestic capability in materials, processing, manufacturing, and qualification, while maintaining diversified and durable international partnerships where domestic supply is geologically or economically infeasible (Edler et al. 2023). Autarky would be the pursuit of complete self-sufficiency, in which every input is supplied domestically and imports are eliminated altogether. That is neither achievable nor desirable for a country whose geology does not contain commercially viable deposits of several of the minerals it needs.

This distinction matters for heavy rare earths and other inputs for which India will remain import dependent. The paper discusses the implications of such an approach for thermoelectrics, which is the direct solid-state conversion of heat into electricity, and of electricity into cooling, in devices with no moving parts. Thermoelectrics is used as a probe case because of its analytical tractability rather than its market size.

The paper makes three contributions: it identifies vulnerabilities in thermoelectric-relevant mineral chains; develops a three-scenario framework that includes the depth of international partnerships; and proposes a politically and financially grounded pathway from research capability to strategic industrial capacity.

2. Capability Requirements and International Benchmarks

A technology-driven India requires capabilities that discussions of *Viksit Bharat* have largely taken for granted. Vision documents and commentaries on the 2047 goal concentrate on macroeconomic targets, digital public infrastructure, the manufacturing share of output, and the demographic dividend (NITI Aayog 2025). The physical base beneath those goals is generally assumed rather than examined: the minerals that must be mined and refined, the materials that must be synthesised to specification, and the devices that must be manufactured, tested, and certified within the country. The omission matters because each of these capabilities takes a decade or more to build and cannot be procured at short notice once a supply disruption is already under way. Recent work on technology sovereignty makes the same point about the distance between a stated ambition and the industrial means of achieving it (Edler et al. 2023).

Four areas are particularly important for materials sovereignty. Below, we describe where India stands in each of these areas today.

A domestic semiconductor ecosystem. India's semiconductor market was valued at about USD 38 billion in 2023 and is projected to exceed USD 100 billion by 2030 (Press Information Bureau 2026a). The ISM, initially backed by an outlay of ₹76,000 crore, has moved into implementation. By July 2026, 12 manufacturing projects across six states had been approved, with committed investment of more than ₹1.64 lakh crore. Semicon 2.0, approved in July 2026 with an outlay of ₹1,27,500 crore, expands support for design, fabrication, advanced packaging, equipment, materials, research, and talent development (Press Information Bureau 2026b).

Critical-mineral autonomy. The NCMM, launched in January 2025 with an expenditure of ₹16,300 crore and expected public-sector investment of ₹18,000 crore over seven years, aims to complete 1,200 domestic exploration projects, auction more than 100 critical-mineral blocks by FY 2030–31, and enable Indian companies to secure at least 50 overseas mining assets (Ministry of Mines 2025). Centres of Excellence have been established at IIT Bombay, IIT Hyderabad, IIT (ISM) Dhanbad, IIT Roorkee, CSIR-IMMT, CSIR-NML, IISc Bengaluru, C-MET Hyderabad, and NFTDC Hyderabad (Press Information Bureau 2025b). A ₹1,500-crore incentive scheme has also been approved for recovering critical minerals from e-waste and end-of-life products (Press Information Bureau 2025a). These are input targets rather than output guarantees, and their limits should be stated plainly. A completed exploration project need not identify an economically mineable deposit, and an auctioned block need not become a producing mine within the mission period; both measure activity at the front of the pipeline rather than delivered supply. The overseas target is more

contingent still, because it depends on which assets host governments choose to release and on what competing bidders are willing to pay. India's experience with overseas hydrocarbon acquisition suggests that equity in a foreign asset does not by itself guarantee delivered volumes at home. Progress against these targets is therefore best read as a measure of effort and seriousness of intent, not as evidence that supply has been diversified.

Energy resilience beyond renewables. The industrial sector accounts for about 45% of India's electricity consumption. NITI Aayog notes that 20–50% of industrial energy input can be lost as waste heat; using a 30% assumption gives an illustrative national estimate of about 160 TWh a year (NITI Aayog 2022). Thermoelectric generators (TEGs) and organic Rankine cycle (ORC) systems can recover part of this resource where site conditions and economics are suitable (He and Tritt 2017).

Strategic technology autonomy. Defence, aerospace, and space systems require specialised materials and devices, including thermoelectric coolers for infrared sensors and high-purity compound semiconductors for radar and communications. Importing is ordinarily a commercial choice. It becomes a security concern when a component performs a mission-critical function, qualified alternatives are unavailable, supply is highly concentrated or subject to export controls, and substitution or requalification cannot occur within an operationally acceptable period. Civilian thermoelectric modules can therefore be sourced through diversified international supply chains, whereas selected defence applications require domestic qualification capability and assured access.

India is not the only country grappling with these challenges. A brief look at how other nations are responding puts India's own efforts in sharper perspective.

2.1 International Policy Benchmarks

The European Union's Critical Raw Materials Act sets benchmarks of at least 10% of annual consumption from domestic extraction, 40% from domestic processing, and 25% from recycling by 2030. It also seeks to limit reliance on any one third country to no more than 65% of annual consumption at a relevant processing stage (European Commission 2024). The value of this benchmark for India lies in linking extraction, processing, recycling, diversification, and project facilitation rather than copying the EU model. Other jurisdictions use instruments such as strategic stockpiles, overseas partnerships, and targeted industrial support, but these must be assessed in their own institutional settings.

Beyond legislative frameworks, project-level programmes can integrate minerals, materials, devices, and markets. The Horizon Europe START project (2022–2026), with a total cost of about €9.19 million and 14 participants, developed a mine-waste-to-thermoelectric-device value chain based on tetrahedrite and validated demonstrator devices (European Commission 2026; START Project 2026). Its final programme linked resource selection, processing, materials characterisation, device fabrication, life-cycle assessment, and market development. The project also established the Sustainable Thermoelectric Alliance, the START European Thermoelectric Systems service company, and a technology marketplace to sustain collaboration beyond the grant period (START

Project 2026). India does not yet have an equivalent coordinated programme linking mineral recovery, materials processing, device fabrication, qualification, and market deployment for thermoelectrics.

These international examples share one feature: they treat minerals, processing, devices, recycling, and markets as a single policy object rather than as separate sectoral responsibilities. India can draw practical lessons from that approach while adapting it to its own resource base, federal structure, and development priorities. Judged against this standard, India's NCMM is an important enabling framework. Its ₹34,300-crore outlay and its targets for exploration, auctions, processing, recycling, skills, and patents establish a broad policy direction (Ministry of Mines 2025; Press Information Bureau 2025a). The next phase can build on this foundation by connecting project development with land access, community engagement, environmental approvals, technology access, offtake, risk capital, and credible benefit-sharing arrangements. The NCMM, ISM, and PLI schemes operate through complementary institutional channels. Stronger coordination can reduce transaction costs and align incentives across the value chain, while state governments, communities, firms, and technical institutions contribute to durable project delivery.

2.2 The Political Economy of Implementation

Critical mineral projects are not simply engineering programmes. They create distributional choices involving land, water, livelihoods, environmental risk, fiscal revenues, and access to downstream value. In Scheduled and forested areas, land acquisition, forest clearance, consultation, rehabilitation, and benefit sharing shape the legitimacy and duration of projects. Centre–state responsibilities add complexity: mineral-bearing states manage local political and administrative conditions, while central policy guides auctions, strategic priorities, and overseas engagement. Delays and litigation may therefore reflect governance failures rather than administrative inefficiency alone.

A viable strategy therefore requires operational safeguards: early and continuing community engagement, transparent social and environmental baselines, independently-monitored rehabilitation and benefit-sharing commitments, and accountable use of District Mineral Foundation resources. Processing and recycling raise parallel concerns, including pollution control, worker safety, and the treatment of informal collectors. These are substantive design constraints, not externalities to be addressed after a project is financed. Recent work on India's critical-mineral transition similarly places supply vulnerability within domestic and global political economy, rather than treating mineral access as a purely geological issue (Tagotra et al. 2024).

Existing District Mineral Foundation (DMF) accountability is not purely aspirational. Under the revised Pradhan Mantri Khanij Kshetra Kalyan Yojana (PMKKKY) guidelines, the DMF Governing Council approves five-year and annual plans. Each DMF must publish its plans, budgets, work orders, meeting minutes, project progress, and annual reports. Its accounts are subject to Comptroller and Auditor General (CAG) audit (on a schedule determined by the CAG) and to an annual audit by a chartered accountant whose report must be placed in the public domain. A State-Level Monitoring

Committee monitors compliance with transparency, audit, and annual-report requirements (Ministry of Mines 2024).

Allocation rules also require a distinction between domestic concessions and overseas acquisitions. Domestic critical-mineral concessions are awarded under the Mineral (Auction) Rules, 2015, rather than through administrative selection of the winning firm. The Central or State Government publishes a notice inviting tender. Bidders first satisfy disclosed eligibility conditions, after which qualified bidders enter a two-stage ascending online auction. The platform automatically identifies the highest final price offer as the preferred bidder, and the State then grants the lease. This process limits discretion over the winner, although publication of block-selection rationales, tender modifications, cancellations, affiliate relationships, and beneficial ownership remains important for detecting capture (Indian Bureau of Mines 2026).

Overseas asset acquisition is not governed by the domestic auction mechanism. Under the policy for Central Public Sector Enterprises, opportunities may arise through host-government processes, direct proposals, qualified merchant bankers, or expressions of interest. The responsible enterprise must undertake a transparent techno-economic evaluation, independent technical, financial, and legal due diligence, and written board consideration before seeking approval (Department of Public Enterprises 2011). Because this route necessarily retains greater judgement, the NCMM should publish country- and asset-selection criteria; disclose intermediaries, beneficial owners, and conflicts of interest; record recusals; publish decision rationales and risk-and-offtake summaries, subject to legitimate commercial confidentiality; and report post-investment performance. These disclosures are not only anti-corruption measures; they are the mechanism through which the mission can establish whether an acquisition has actually improved India's access to minerals. An overseas asset secures supply only if its output can be delivered to India at a volume and price that were understood at the time of purchase. The characteristic failure in negotiated transactions is not theft but mispricing: an enterprise acquires equity in a project whose output is already committed to other buyers, whose operating costs are understated, or whose host-country approvals are incomplete. Publishing selection criteria, offtake terms, and post-investment performance therefore serves the supply objective directly, because it is what allows an acquisition that adds material to India's supply to be distinguished from one that only adds an asset to a balance sheet.

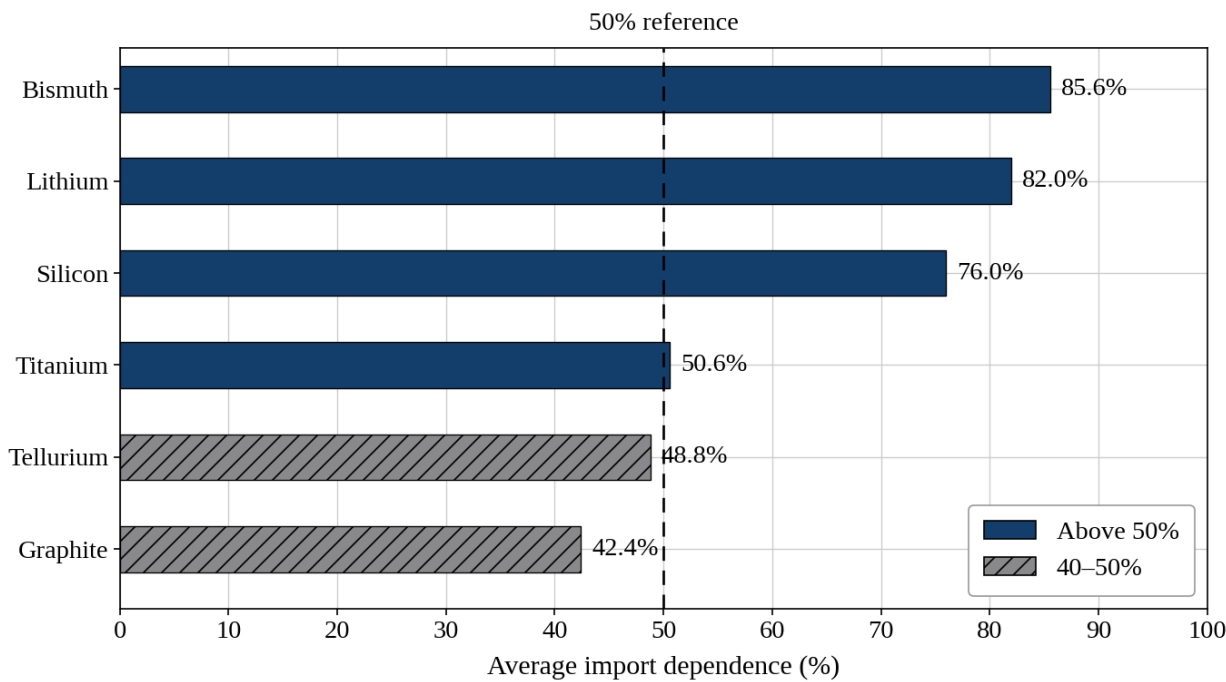
3. Quantifying India's Mineral Vulnerability

Before turning to scenarios for India's deep-tech future, it is useful to identify where mineral vulnerability is most acute. The aggregate picture of import dependence is concerning, but it masks important variation among minerals in both, the degree of dependence on China and the nature of the strategic risk.

A recent assessment by the Takshashila Institution examined India's import dependence across the 30 critical minerals identified by the Ministry of Mines in 2023 (Shetty 2024). The study identifies

six minerals for which India’s average dependence on Chinese imports exceeds 40%: bismuth (85.6%), lithium (82%), silicon (76%), titanium (50.6%), tellurium (48.8%), and graphite (42.4%). Germanium falls outside this comparison: India is fully import dependent for germanium, but that figure covers imports from all sources and no China-specific share is reported (Ministry of Mines 2023). Figure 1 illustrates these dependence levels.

Figure 1. India’s average import dependence on China for the six critical minerals with dependence above 40%, 2019–2024.



Source: Author’s visualisation based on Shetty (2024).

Table 1 provides a more detailed view by mapping each mineral to its vulnerability classification and the principal route by which that dependence could be reduced. The three vulnerability classes follow a simple convention. Import-dependent denotes a mineral that India does not produce at commercial scale, so that supply is wholly external. Critical denotes a mineral for which dependence is high but domestic resources or production capacity exist, so that the constraint lies in processing capacity and investment rather than in the absence of the resource. Strategic denotes a mineral for which dependence is high, alternative suppliers are few, and the end use is essential to a defence, space, or priority industrial application, so that an interruption cannot be absorbed by paying a higher price. Bismuth and tellurium, the two minerals most directly relevant to conventional thermoelectric modules, both fall in the strategic-vulnerability group and show high dependence on imports from China.

Table 1. India's Import Dependence on China for Thermoelectric-Relevant Critical Minerals.

Mineral	Average China Import Dependence (2019–2024)	Key Applications	Vulnerability Class	Route to Reduced Dependence
Germanium	Not reported*	Silicon-germanium (SiGe) thermoelectrics, infrared (IR) optics, fibre optics	Import-dependent	No viable domestic route; supplier diversification and strategic stocks
Bismuth	85.6%	Bismuth telluride (Bi_2Te_3) thermoelectric modules, pharmaceuticals	Strategic	By-product recovery from lead and tungsten smelting, and from pharmaceutical waste; both at pilot stage
Lithium	82.0%	EV batteries, energy storage	Critical	Overseas equity and long-term offtake; domestic resources at exploration stage
Silicon	76.0%	Semiconductors, solar PV, silicon-germanium (SiGe) thermoelectrics	Critical	Domestic production exists; the gap is high-purity refining capacity
Titanium	50.6%	Aerospace alloys, defence, pigments	Critical	Domestic ilmenite is ample; the gap is sponge and alloy processing
Tellurium	48.8%	Bismuth telluride (Bi_2Te_3) thermoelectric modules, cadmium telluride (CdTe) solar PV	Strategic	By-product recovery from anode slimes at Indian copper refineries
Graphite	42.4%	EV anodes, refractories, lubricants	Strategic	Reserves are adequate; the gap is purification and anode-grade processing

Source: Author's compilation based on Shetty (2024) and Ministry of Mines (2023). *Shetty (2024) does not report a China-specific share for germanium; India is 100% import dependent for germanium across all sources (Ministry of Mines 2023). All other figures are average shares of Chinese imports, 2019–2024.

4. Three Scenarios for 2047

The vulnerability data raise a practical question: how might India's position in materials and devices evolve under different policy and market conditions? The scenarios below are heuristic tools, not forecasts. They vary four drivers: institutional coordination, commercialisation and finance, entrepreneurial mobilisation, and the depth of international partnerships. They also distinguish the domestic capability that India can realistically build from inputs for which diversified external access will remain necessary. Table 2 summarises the scenarios across seven indicators.

4.1 Scenario A: Business-as-Usual – Continued Import Dependence

In this trajectory, current missions make useful progress within their existing mandates, while integration across the value chain develops gradually. Critical minerals continue to be sourced mainly through China-centred supply chains, and semiconductor fabrication remains concentrated at nodes suited to domestic consumer electronics. Thermoelectrics remains largely a research and early-demonstration field. This scenario preserves valuable institutional and scientific foundations but leaves gaps in advanced manufacturing, qualification, and strategic supply resilience.

4.2 Scenario B: Partial Sovereignty – Islands of Success

In this scenario, major missions deliver visible gains in exploration, overseas partnerships, semiconductor fabrication, and selected strategic technologies. India achieves domestic production of 15 critical minerals, as targeted by the NCMM (Ministry of Mines 2025). Semiconductor fabs produce chips in the 28–65 nm range, while ISM 2.0 advances a roadmap towards 3 nm capability by 2035 (Press Information Bureau 2026a). Khanij Bidesh India Limited (KABIL)'s overseas acquisitions in Argentina and Australia strengthen access to lithium and cobalt (VIF 2025). Thermoelectrics in this scenario becomes visible without becoming a supply chain. Pilot-scale module assembly is established at one or two institutional or start-up sites, most plausibly for cooling and sensor applications where volumes are small and qualification requirements are modest. Materials continue to be imported as ingots or powders, module-level qualification for defence and space use remains outside India, and recovery of bismuth and tellurium from domestic residues stays at laboratory scale. This is the island-of-success pattern in miniature: real capability at the bench and at pilot scale, with the transition to qualified commercial production still unmade. The next requirements are sustained coordination among MeitY, the Ministry of Mines, the Defence Research and Development Organisation (DRDO), the Indian Space Research Organisation (ISRO), and the Department of Atomic Energy (DAE); pilot-to-production support for university spin-outs; and finance structures for appropriately selected micro, small and medium enterprise (MSME) waste-heat projects.

4.3 Scenario C: Strategic Autonomy with Managed Interdependence

In this trajectory, India develops robust domestic capability in priority segments: exploration and recovery where resources are available, processing and recycling where domestic feedstocks are viable, module manufacturing in selected applications, and national qualification capacity for strategic devices. It does not seek comprehensive self-sufficiency. Heavy rare earths and other inputs without economically viable domestic sources remain import dependent, so resilience rests on diversified suppliers, strategic stocks, substitution, recycling, and long-term partnerships.

The strategic value of thermoelectrics also extends beyond commercial waste-heat applications. Radioisotope thermoelectric generators (RTGs) provide reliable electrical power by converting decay heat into electricity without moving parts, a capability the National Aeronautics and Space Administration (NASA) has used for spacecraft operating where solar power is constrained. ISRO's published research requirements likewise identify thermoelectric materials for RTGs that can supply spacecraft power when solar power is unavailable.

India's immediate opportunity is therefore to strengthen the enabling capabilities that future strategic missions require: high-temperature materials research, module reliability, thermal management, radiation-aware testing, and domestic qualification. A focused mission-mode programme would support long-horizon national-security and space objectives while maintaining appropriate safeguards, international cooperation, and realistic technology milestones (NASA 2023; ISRO 2024).

International engagement is therefore part of success rather than evidence of failure. India's membership in the Minerals Security Partnership, KABIL's agreement for five lithium-brine blocks in Argentina, and the India-Australia Critical Minerals Investment Partnership illustrate the types of institutional relationships through which external access can be made more reliable. Domestic thermoelectric manufacturing serves civilian niches and selected strategic applications, supported where appropriate by licensing, joint ventures, and jointly developed process know-how. A new generation of firms builds commercially viable capabilities in recovery, processing, materials, modules, and systems integration.

What separates Scenario B from Scenario C is a combination of execution, finance, and partnership quality. Research capability remains necessary, but it is insufficient without investable projects, credible offtake, access to process technology, social licence, and coordinated qualification pathways. This scenario measures autonomy as the ability to make and sustain informed choices under disruption, rather than as the elimination of imports.

Table 2. Comparative Summary of Three Scenarios for Deep-Tech Sovereignty by 2047.

Indicator	Scenario A: Business-as-Usual	Scenario B: Partial Sovereignty	Scenario C: Strategic Autonomy with Managed Interdependence
Critical-mineral resilience	Limited domestic processing; concentrated imports	Selective domestic production; partial diversification	Domestic depth in priority chains; diversified imports for structurally unavailable inputs
Semiconductor capability	Mature-node capability; high import dependence	28–65 nm fabs; ISM 2.0 roadmap active	Advanced-node capability; diversified international partnerships
TE device manufacturing	No domestic production at commercial scale	Pilot-scale modules; research-to-market gap remains	Qualified commercial manufacturing in selected applications
MSME waste-heat recovery	Limited recovery	Partial adoption, mainly in large plants	Selective, cost-effective TEG/ORC deployment across MSMEs
Defence / aerospace autonomy	Imported thermoelectric coolers and power systems	Selected indigenous devices; limited qualification	Qualified thermoelectric and compound-semiconductor devices
Institutional coordination	Fragmented; ministry silos	Improving, with periodic inter-agency reviews	Integrated mandate paired with social, environmental, and finance safeguards
International partnerships	Transactional purchasing; concentrated suppliers	Several bilateral arrangements; limited project depth	Institutionalised project, technology, offtake, and recycling partnerships

Source: Author's compilation based on Ministry of Mines (2025) and Press Information Bureau (2025a, 2026a, 2026b).

5. Thermoelectrics and Critical Minerals: A Probe Case

The scenarios above operate at a high level of abstraction. This section turns to thermoelectrics as a bounded probe case. Thermoelectrics is not presented as India's largest or most commercially mature strategic sector. Instead, this small and emerging field makes the links among minerals, materials, manufacturing, finance, and end-of-life recovery unusually visible within a tractable value chain.

5.1 Case Selection: Why Thermoelectrics?

Six features make thermoelectrics a useful probe. First, its value chain is compact enough to analyse from feedstock to module and application in one paper. Second, key material systems expose concentrated upstream dependencies, particularly for bismuth, tellurium, antimony, and germanium. Third, the field displays a sharp research-to-manufacturing asymmetry: India has active laboratories and device-relevant expertise, while commercial module production remains limited. Fourth, the market's early stage offers an entry window before incumbent scale becomes decisive, but high-value niches must still support viable manufacturing. Fifth, thermoelectric technologies span civilian cooling, sensors, distributed waste-heat applications, and selected strategic uses. Sixth, the field connects primary supply to recovery and substitution because conventional materials rely on scarce elements and recycling remains an unresolved industrial challenge (Bahrami et al. 2020).

These criteria are more discriminating than the general observation that a technology needs minerals, capital, and coordination. Permanent magnets and motors are crucial sectors, and recent supply disruptions underline their importance. They are, however, larger, more mature, and already the subject of substantial policy attention. Their supply chains and end-use markets also introduce several interacting industrial layers that would obscure this paper's purpose.

Thermoelectrics offers a deliberately narrow test of whether India can translate a scientifically capable but commercially underdeveloped materials field into selective domestic capability through partnerships, finance, manufacturing, and responsible governance. Its niche character is therefore part of the research design, not a proxy for national market scale. Thermoelectric technologies are most credible where competing technologies are poorly suited, including local cooling, remote power, sensors, and selected waste-heat settings (Vining 2009; Zoui et al. 2020).

Thermoelectric energy conversion, the direct and solid-state interconversion of heat and electricity through the Seebeck and Peltier effects, provides a useful lens for the broader materials and device agenda. Indian institutions have built research strengths across oxide thermoelectrics, bismuth telluride and antimony telluride chalcogenides, copper-arsenic-selenium glasses, flexible and paper-based devices, photothermoelectrics, and Peltier-based biomedical and cold-chain applications. The thermoelectric figure of merit (ZT), which governs conversion efficiency, has improved from approximately 1.0 to over 2.6 in laboratory settings over the past two decades (Snyder and Toberer 2008; Zhao et al. 2014; He and Tritt 2017). This research base creates a platform for application-specific translation. C-MET, IIT Madras, IIT Bombay, JNCASR, and DRDO's Defence Laboratory at Jodhpur can connect materials research with module engineering, testing, qualification, and market-facing partnerships to build an Indian thermoelectric product pipeline.

Supply-chain concentration creates a clear case for India to combine diversified sourcing with domestic learning in selected thermoelectric materials and modules. Commercial bismuth telluride (Bi_2Te_3) modules are concentrated in Asian supply chains, while tellurium is a scarce by-product with competing uses in solar photovoltaics and thermoelectric devices (United States Geological Survey 2024). These conditions support the evaluation of alternative material pathways alongside

partnership-based access to established supply chains. European programmes have advanced tellurium-free tetrahedrite ($\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$), a copper-antimony sulfosalt that can be recovered from mine tailings. Tetrahedrite-group minerals have also been documented at Rajpura-Dariba in Rajasthan (Basu et al. 1981). This provides a basis for India to assess a mine-waste-to-thermoelectric pathway through staged geological, processing, and device-validation work.

India also has additional resource and secondary-material pathways that warrant systematic assessment. Indian Bureau of Mines reviews report that selenium and tellurium can be recovered as by-products from copper-refining anode slimes, while tellurium may also occur in lead-refinery skimmings and smelter dust. The same reviews identify inferred antimony resources in Himachal Pradesh and a by-product recovery route from lead-zinc smelting residues. In the Khetri Copper Belt, Rajasthan, cobalt-rich pyrite and bismuth-bearing mineral inclusions have been documented.

These observations establish geological and processing leads rather than proven thermoelectric-feedstock reserves. They justify a staged programme of resource characterisation, metallurgical testing, life-cycle assessment, and techno-economic validation before investment in commercial supply chains (Indian Bureau of Mines 2020, 2022; Baidya et al. 2021).

Pharmaceutical waste offers a further research-led circularity pathway for bismuth. Bismuth subsalicylate, used in gastrointestinal formulations, is a bismuth-rich active pharmaceutical ingredient. Its composition makes segregated pharmaceutical waste a potential high-grade secondary feedstock, provided that collection, traceability, contamination control, worker safety, and compliant treatment are established. India's biomedical-waste infrastructure could support a pilot-scale assessment, but recoverable volumes, separation performance, economics, and environmental safeguards remain to be demonstrated. A targeted pharmaceutical-mining pilot led by C-MET, with CSIR laboratories, licensed waste handlers, and pharmaceutical partners, could establish this evidence base before any scale-up decision (Svensson Grape et al. 2022; Griffith et al. 2021).

Table 3 maps the critical minerals used in thermoelectric technologies against India's supply-chain position and the NCMM's coverage. Most major thermoelectric material systems depend on minerals for which China has a major or dominant role in mining, refining, or processing (Shetty 2024; United States Geological Survey 2024). India has included each of these minerals in its 2023 critical-minerals list.

Table 3. Critical Minerals for Thermoelectric Technologies: India's Supply-Chain Position.

Mineral	Key TE Application	China's Position in Global Supply	Included in India's 2023 Critical-Minerals List	Covered by NCMM	Typical Primary Source or Feedstock
Tellurium (Te)	Bi ₂ Te ₃ modules (low temperature)	Major producer and refiner	✓	✓	Copper-refining by-product
Bismuth (Bi)	Bi ₂ Te ₃ and bismuth-antimony-telluride (BiSbTe) alloys	Dominant producer	✓	✓	Lead and tungsten smelting by-product
Antimony (Sb)	Antimony telluride (Sb ₂ Te ₃) and <i>p</i> -type thermoelectric legs	Major producer	✓	✓	Dedicated ores and lead by-products
Selenium (Se)	Copper-arsenic-selenium glasses and lead selenide (PbSe)	Major refiner	✓	✓	Copper-refining by-product
Germanium (Ge)	SiGe high-temperature modules	Dominant supplier	✓	✓	Zinc ores and coal fly ash
Gallium (Ga)	Gallium nitride (GaN) compound semiconductors	Dominant supplier	✓	✓	Bauxite and aluminium refining
Indium (In)	Indium tin oxide (ITO) coatings and indium gallium arsenide (InGaAs) sensors	Major refiner	✓	✓	Zinc-refining by-product
REEs (Nd, Dy)	Oxide thermoelectrics and permanent magnets	Dominant processor	✓	✓	Monazite and beach sands

Source: Author's compilation based on Ministry of Mines (2023), Shetty (2024), United States Geological Survey (2024), and Rowe (2005).

India's industrial waste heat presents a set of site-specific opportunities for thermoelectric generators. NITI Aayog's illustrative assumption gives a national estimate of about 160 TWh a year, but this is not the technical or economic potential available to TEGs (NITI Aayog 2022). TEGs are

solid-state devices and may suit small, distributed, or maintenance-sensitive installations, including some brick kilns, glass furnaces, food-processing plants, and small steel foundries. Deployment should follow a transparent comparison of heat temperature, duty cycle, installation cost, expected energy yield, and alternatives such as direct heat reuse, efficiency improvements, and ORC systems. Waste-heat recovery is therefore a test bed for selected applications, not evidence that thermoelectrics will become a large-volume power-generation industry. Commercialisation depends on application-specific performance, finance, and manufacturing capability (Zoui et al. 2020).

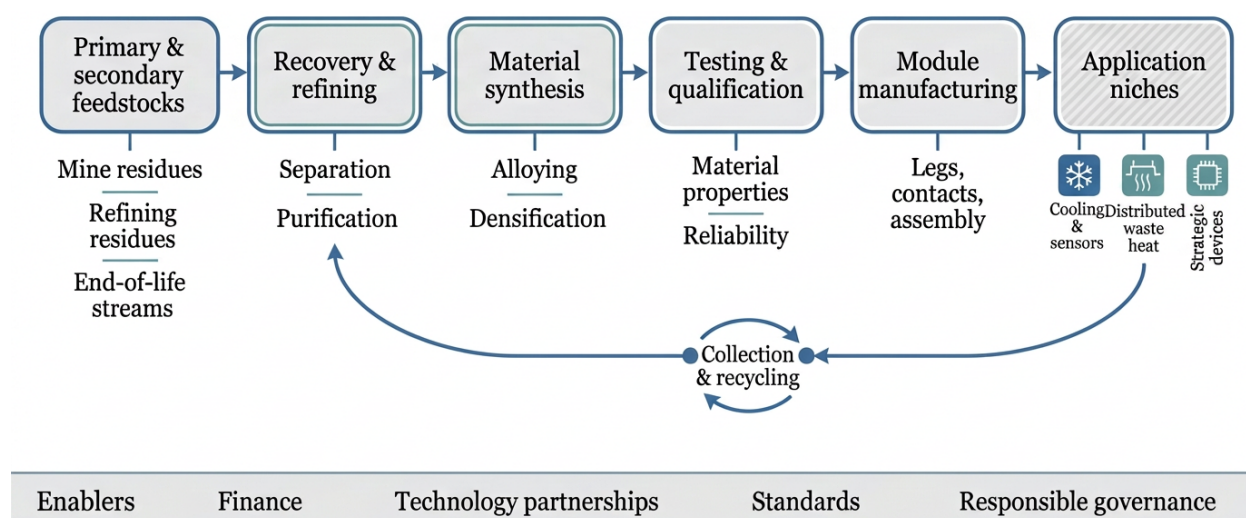
Defence and space applications add a distinct but bounded strategic rationale. Thermoelectric devices are used in infrared-sensor cooling, portable power, and remote-power applications. In mission-critical systems, qualification is jurisdiction-specific: a device accepted in a civilian supply chain or by an allied country may still require domestic testing, documentation, and requalification. The policy implication is targeted domestic capability in design, qualification, repair, and assured supply for specified defence applications, not blanket substitution of all imported thermoelectric products. Civilian markets can continue to use internationally certified modules and diversified partnerships.

Thermoelectric technologies therefore warrant selective capability building rather than treatment as a mass-market power-generation industry. Their policy value arises where solid-state operation, compactness, low maintenance, precise temperature control, remote operation, or jurisdiction-specific qualification creates a clear advantage. For instance, Peltier coolers can provide localised cooling for infrared detectors, analytical instruments, optical and electronic components, and selected medical or laboratory equipment.

India's appropriate objective is capability in application-specific design, integration, testing, repair, and qualified manufacturing, supported by technology partnerships. Deployment should remain subject to technical and economic comparison with alternative cooling and waste-heat solutions. Figure 2 illustrates the value chain from critical minerals to deployed systems.

A circular-economy opportunity also exists. Tellurium and bismuth may be recoverable from domestic refining residues and selected end-of-life streams, although feedstock quality, collection, process economics, and environmental compliance will determine commercial viability. The critical-mineral recycling incentive scheme creates a policy opening, but incentives should reward verified mineral recovery and support formal processors that can work with, rather than displace, informal collection networks. Recycling cannot provide near-term sufficiency for materials embedded in long-lived products; it should be one component of a diversified supply strategy. For strategic devices, recovered material must satisfy traceability, purity, reliability, and module-level qualification requirements. India can develop these capabilities through international technology partnerships rather than isolation.

Figure 2. Thermoelectric value chain from primary and secondary feedstocks to application niches, with a recycling loop returning recovered material to refining.



Source: Author's conceptualisation.

Value-added manufacturing can connect material recovery with strategic and commercial value. It requires access to module designs and process knowledge, equipment for densification (the consolidation of thermoelectric powders into dense, mechanically robust ingots) and for module assembly, trained technicians, testing standards, and an accredited qualification pathway. Licensing and joint ventures with established module producers, government-to-government technology cooperation, shared pilot lines, and a national test and certification facility anchored in institutions such as C-MET and the National Physical Laboratory (NPL) can build these capabilities through staged learning and investment. The finance mechanisms discussed in Section 6.1 can link them to early offtake and milestone-based support for scale-up.

The scale of the circular-economy opportunity is often underestimated. NITI Aayog estimates that India generated 6.19 million tonnes of e-waste in 2024 and could generate 14 million tonnes by 2030 (NITI Aayog 2026). This stream may contain recoverable quantities of tellurium, bismuth, indium, gallium, and rare earth elements, but recoverable volumes, collection efficiency, process economics, and environmental performance require validation. A dedicated e-waste-to-strategic-minerals programme could link the NCMM recycling incentive with informal-sector collection networks and compliant formal-sector processing. Such a programme could support mineral security, e-waste management, and MSME employment, provided that incentives are tied to verified recovery and safe treatment.

The EU's START project provides an instructive international parallel. It developed an integrated circular pathway from mine-waste tetrahedrite to thermoelectric materials and demonstrator devices. Its innovation agenda and roadmap connect raw materials, processing, production, applications, end-of-life recovery, and wider political, economic, social, technological, environmental, and legal

considerations (European Commission 2026; START Project 2026). The relevant lesson is integrated programme design: geological sourcing, materials processing, device engineering, life-cycle assessment, and commercialisation can be connected through a coordinated learning pathway that builds on India's existing missions and pilot capabilities.

6. Entrepreneurial Pathways and Future Trends

The thermoelectrics case illustrates a broader opportunity. Where India's deep-tech research base intersects with a strategic materials need, entrepreneurial pathways can connect scientific capability with market-facing applications. Several concrete pathways illustrate how the existing ecosystem can be extended.

MSME-scale waste-heat-to-power enterprises. TEGs could create a complementary market segment where small, distributed, and maintenance-sensitive installations are poorly served by turbine-based systems. Entrepreneurs could combine modules, application-specific heat exchangers, monitoring, and energy-as-a-service contracts to reduce upfront costs. Deployment should be assessed site by site against heat temperature, duty cycle, competing technologies, and financing cost. No aggregate estimate of annual CO₂ savings is offered because a credible national estimate requires a technology-specific deployment model rather than a gross waste-heat figure.

Critical-mineral recovery and processing ventures. The NCMM's emphasis on unconventional domestic sources and recycling creates a platform for start-ups specialising in hydrometallurgical and electrochemical extraction from secondary feedstocks. Tellurium recovery from copper anode slimes, bismuth recovery from lead-smelting residues, and rare-earth recovery from end-of-life magnets offer identifiable venture pathways. University spin-outs from the NCMM's Centres of Excellence can advance these opportunities when technical development is paired with pilot-scale access, offtake partnerships, and efficient intellectual-property support through the Indian Patent Office. These arrangements can help promising materials technologies move from filing and validation to investment and commercial deployment (Press Information Bureau 2025a).

Defence and aerospace deep-tech companies. India's expanding defence-industrial base, supported by the iDEX (Innovations for Defence Excellence) programme, provides a growing market for specialised materials and devices. Thermoelectric coolers for infrared focal-plane arrays, radiation-tolerant compound semiconductors, and high-temperature thermoelectric modules for aero-engine health monitoring are representative product categories in which Indian start-ups could build niche capabilities.

Deep-tech platform companies. As India's semiconductor-design ecosystem matures under the Design-Linked Incentive scheme with 24 start-ups supported and about ₹430 crore in venture capital attracted as of January 2026 – firms can increasingly integrate materials science, device design, and systems engineering (Press Information Bureau 2026a). A thermoelectric-device company could design modules, source material through domestic circular streams and diversified partnerships, and

serve both industrial and strategic applications. Such platform firms would link research, manufacturing, and services around specific customer needs.

India's expanding innovation-finance ecosystem can be adapted to the longer development cycles of deep-tech hardware and materials ventures. Patient capital, technical milestones, and strategic offtake can help research-led firms progress from laboratory validation to manufacturing scale-up. Subject to the governance safeguards set out in Section 6.1, a dedicated deep-tech materials fund co-financed by MeitY, the Ministry of Mines, and private investors could complement existing innovation instruments. International co-investment and applied-research models offer useful design lessons, but any Indian mechanism must fit domestic institutions and accountability requirements.

6.1 Financing the Value Chain

The financing gap is not simply a shortage of venture capital. Each stage of the value chain carries a different risk and therefore requires a different instrument. Exploration faces geological uncertainty and should rely on public geological data, grants, and risk-sharing vehicles rather than conventional venture finance. Mining projects require long-tenor capital and may use viability-gap support, royalty or streaming structures, and public co-investment where strategic value is demonstrable. Processing projects face high capital expenditure, uncertain offtake, and volatile international prices. They may require capital-expenditure support, milestone-based production payments, price-support instruments, and credible anchor offtake.

Recycling requires incentives tied to verified recovery rather than collection alone, working-capital support for formal processors, and arrangements that connect informal collection networks with safe and compliant facilities. Value-added manufacturing requires patient debt and equity, first-loss or partial credit guarantees, purchase commitments from public and strategic buyers, and technology-transfer partnerships that reduce process risk.

This instrument map replaces a generic call for a fund with a portfolio of risk-sharing tools across mining, processing, recycling, and manufacturing. Research on India's policy reforms similarly identifies exploration finance, advance market commitments, overseas partnerships, recycling, and an integrated value-chain strategy as complementary rather than substitutable measures (Jain 2024).

If established, a National Deep-Tech Materials Fund should be a ring-fenced, professionally managed co-investment vehicle rather than a discretionary grant window.

- Sponsoring ministries should set its mandate and risk budget but should not select individual recipients.
- Project selection should use published eligibility and scoring criteria, competitive calls, independent technical and financial appraisal, and an investment committee with a majority of non-ministerial members.
- Conflict-of-interest and beneficial-ownership disclosures, recorded recusals, and documented reasons for awards should be mandatory.

- Disbursement should be tied to verified milestones, with portfolio concentration limits, public reporting of commitments and outcomes subject to legitimate commercial confidentiality, annual independent audit, CAG audit where legally applicable, and periodic ex post evaluation.
- A published complaints and review process should permit challenges to procedural irregularities.

These controls reduce capture risk, but they do not substitute for permitting, community consent, technology access, or commodity-price management. Table 4 translates this approach into a stage-specific instrument map.

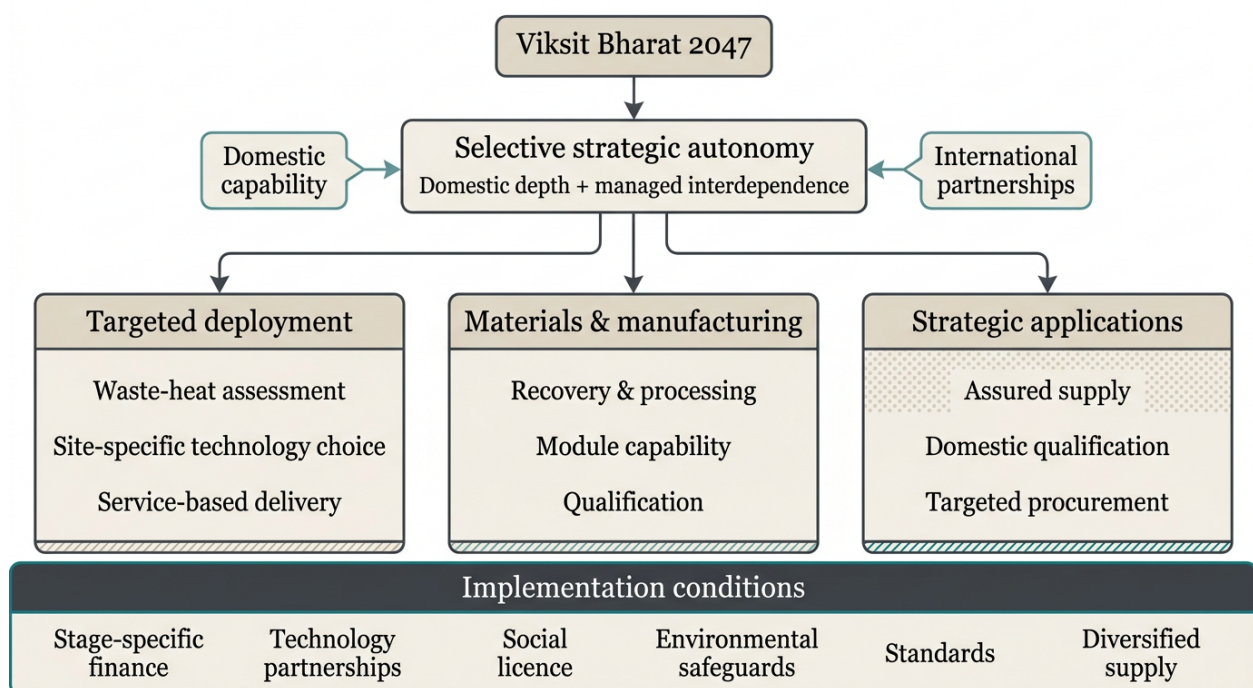
Table 4. Stage-specific financing and implementation instruments for the thermoelectric and critical-minerals value chain.

Value-chain stage	Core risk	Appropriate instruments	Implementation conditions
Exploration	Geological uncertainty and long lead times	Public geoscience, exploration grants, risk-sharing vehicles	Transparent data and credible environmental baselines
Mining and feedstock supply	Capital intensity, permitting, community consent	Capital-expenditure support, milestone-based production payments, price-risk instruments, anchor offtake	Social licence, benefit-sharing arrangements, rehabilitation, regulatory compliance
Processing and refining	High capex, price volatility, uncertain offtake	Capex support, milestone-based production payments, price-risk instruments, anchor offtake	Social licence, benefit-sharing arrangements, rehabilitation, and regulatory compliance
Recycling and secondary recovery	Variable feedstock, collection costs, working-capital constraints	Verified-recovery incentives, working-capital support, credits linked to extended producer responsibility (EPR)	Safe formal processing linked to informal collection networks
Module manufacturing and system integration	Scale-up, qualification, technology access, and demand risk	Patient debt and equity, first-loss guarantees, purchase commitments, shared pilot lines	Licensing or joint ventures, standards, test facilities, workforce, application-specific offtake

7. A Three-Pillar Framework for Selective Strategic Autonomy

Drawing on the analysis above, this paper proposes a three-pillar framework for selective strategic autonomy and deep-tech entrepreneurship within Viksit Bharat 2047. The framework treats domestic capability, responsible implementation, and managed international interdependence as complementary. Figure 3 provides a visual summary.

Figure 3. Framework for selective strategic autonomy under Viksit Bharat 2047, combining domestic capability with managed international interdependence.



Source: Author's conceptualisation.

Pillar 1: Industrial Waste-Heat Deployment

This pillar treats India's industrial waste heat as a site-specific resource for TEGs, ORC systems, and other recovery technologies. NITI Aayog's illustrative assumption gives a scale of about 160 TWh a year, but technically and economically recoverable potential will be lower and technology-specific (NITI Aayog 2022). Policy instruments could include Bureau of Energy Efficiency-led waste-heat audits for energy-intensive MSMEs, concessional loans or partial credit guarantees for suitable installations, and after technical validation – eligibility for energy-savings certificates under the Perform, Achieve and Trade (PAT) framework (Bureau of Energy Efficiency 2015).

Pillar 2: Indigenous Critical-Mineral Capability

This pillar builds on the NCMM's architecture to develop end-to-end domestic capability for thermoelectric-relevant minerals: tellurium, bismuth, antimony, selenium, germanium, gallium,

indium, and selected rare earths (see Tables 1 and 3). Key interventions include fast-tracking the auction of critical-mineral blocks; establishing pilot-to-commercial-scale processing at NCMM Mineral Processing Parks; incentivising secondary recovery from copper, lead, zinc, and aluminium refining streams; and creating a National Critical Minerals Stockpile for at least five minerals (Ministry of Mines 2025).

Pillar 3: Targeted Defence and Aerospace Applications

This pillar establishes a coordinated MeitY–DRDO–ISRO–DAE programme for the indigenous development of strategic thermoelectric and semiconductor devices. It includes joint technology development for high-performance thermoelectric coolers, generators, and radioisotope thermoelectric-generator modules; qualification and certification pathways for Indian-manufactured devices; iDEX-funded deep-tech challenges that target specific device needs; and co-location of university research groups with DRDO and ISRO device-testing facilities.

8. Specific Policy Recommendations

The three-pillar framework provides strategic architecture. The following recommendations show how existing missions and institutions can strengthen project development, capability building, and partnership-based delivery.

Financing: Create a stage-specific financing window rather than a single undifferentiated venture fund. The window should combine exploration grants; viability-gap or risk-sharing support for strategic mining; capital-expenditure and price-risk instruments for processing; recovery-linked incentives for recycling; and patient debt, first-loss guarantees, and anchor offtake for module manufacturing.

A catalytic national fund can co-invest with private capital after defined technical, environmental, and commercial milestones. Any such fund should use the governance safeguards specified in Section 6.1: ministries should set the mandate, while project selection rests with an independent investment committee that applies published criteria, conflict-of-interest rules, milestone-based disbursement, audited reporting, and ex post evaluation.

Coordination and legitimacy: Create a mine-to-module pilot under the NCMM, using thermoelectrics as a bounded demonstration case. Its governance should include affected state agencies, environmental and labour regulators, community-facing institutions, buyers, and technical organisations. A three-year timetable should be treated as a monitored learning process, with public milestones for consent, approvals, material quality, module performance, offtake, and social and environmental outcomes. It should not be presented as proof that coordination alone can resolve implementation challenges.

Technology and manufacturing: Support shared pilot lines, licensing and joint ventures, module-assembly equipment, workforce development, and a national testing and qualification facility. These investments can enable value-added manufacturing and reduce the gap between domestic materials

research and reliable commercial modules. Defence applications should use domestic qualification and assured procurement for specified mission-critical components; civilian producers should remain free to use international certification and partnership pathways.

Deployment: Require standardised waste-heat audits for energy-intensive MSMEs and make the results available through a secure project-development platform. This would create a demand pipeline while allowing TEG proposals to compete transparently with ORC systems, efficiency improvements, and other recovery options.

Supply security and partnerships: Use targeted stocks, recycling, substitution, and diversified procurement for materials with limited domestic supply. Institutionalise project-level partnerships through the Minerals Security Partnership, KABIL, and bilateral arrangements such as the India–Australia Critical Minerals Investment Partnership. The objective is a resilient portfolio of domestic and international sources, not self-sufficiency in every mineral.

9. Conclusion

India's technological future depends on the materials base that supports its digital, industrial, and strategic ambitions. Capability in selected minerals, advanced processing, recycling, manufacturing, and device qualification can create industrial learning and strengthen resilience. Selective strategic autonomy therefore rests on a balanced portfolio of domestic depth, diversified supply, durable partnerships, strategic stocks, substitution, and targeted circular recovery.

The scenarios are not forecasts; they clarify choices. India has already created important institutional foundations through the NCMM, ISM, PLI schemes, the iDEX programme, and Centres of Excellence. The next phase can connect these foundations to credible finance, technology access, qualified manufacturing, environmental and social governance, and demand-side offtake. This integration can convert policy ambition and research strength into durable capability in selected priority segments.

Thermoelectrics is an appropriate probe case because the field is narrow enough to bring these interfaces into view. India has an active research base, material dependencies, identifiable high-value niches, and several circularity leads, including mine waste, metallurgical by-products, end-of-life devices, and pharmaceutical waste streams. These leads require systematic resource characterisation, responsible collection, metallurgical testing, life-cycle assessment, and techno-economic validation before commercial deployment. The case shows how a research-capable country can build selective capability through managed interdependence without reproducing every stage of a global value chain domestically. It also highlights the long-term importance of high-temperature materials, module reliability, thermal management, and qualification for future strategic and space-power applications. The lessons can inform other materials sectors by clarifying the project-development, financing, partnership, governance, and mission-oriented arrangements needed for durable delivery.

References

- Bahrami, Amin, Gabi Schierning, and Kornelius Nielsch. 2020. "Waste Recycling in Thermoelectric Materials." *Advanced Energy Materials* 10 (19): 1904159. <https://doi.org/10.1002/aenm.201904159>.
- Baidya, Abu Saeed, Atlanta Sen, Dipak C. Pal, and Dewashish Upadhyay. 2021. "Ore-Forming Processes in the Khetri Copper Belt, Western India: Constraints from Trace-Element Chemistry of Pyrite and C–O Isotope Composition of Carbonates." *Mineralium Deposita* 56 (5): 957–974. <https://doi.org/10.1007/s00126-020-01018-z>.
- Basu, K., N. S. Bortnikov, A. Mookherjee, N. N. Mozgova, and A. I. Tsepun. 1981. "Rare Minerals from Rajpura-Dariba, Rajasthan, India. III. Plumbian Tetrahedrite." *Neues Jahrbuch für Mineralogie – Abhandlungen* 141 (3): 280–289.
- Bureau of Energy Efficiency. 2015. "Waste Heat Recovery." In *Energy Efficiency in Thermal Utilities: Guide Book for National Certification Examination for Energy Managers and Energy Auditors*, Chapter 8. Ministry of Power, Government of India. <https://beeindia.gov.in/sites/default/files/2Ch8.pdf>.
- Department of Public Enterprises. 2011. "Policy for Acquisition of Raw Material Assets Abroad by Central Public Sector Enterprises (CPSEs)." Office Memorandum No. 16(4)/2010-GM, October 24. Government of India. <https://www.dpe.gov.in/static/uploads/2025/07/8da637f3e79386a4065bc8bdf1dfb327.pdf>.
- Edler, Jakob, Knut Blind, Henning Kroll, and Torben Schubert. 2023. "Technology Sovereignty as an Emerging Frame for Innovation Policy. Defining Rationales, Ends and Means." *Research Policy* 52 (6): 104765. <https://doi.org/10.1016/j.respol.2023.104765>.
- European Commission. 2024. "Critical Raw Materials Act." Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en.
- European Commission. 2026. "Sustainable Energy Harvesting Systems Based on Innovative Mine Waste Recycling (START)." CORDIS, Project 101058632. <https://cordis.europa.eu/project/id/101058632>.
- Global Trade Alert. 2025. "China's Export Controls on Critical Raw Materials, Including Rare Earths." <https://globaltradealert.org/blog/chinese-export-controls-on-critical-raw-materials-inventory>.
- Svensson Grape, Erik, Victoria Rooth, Mathias Nero, Tom Willhammar, and A. Ken Inge. 2022. "Structure of the Active Pharmaceutical Ingredient Bismuth Subsalicylate." *Nature Communications* 13: 1984. <https://doi.org/10.1038/s41467-022-29566-0>.
- Griffith, Darren M., Hongyan Li, Melissa V. Werrett, Philip C. Andrews, and Hongzhe Sun. 2021. "Medicinal Chemistry and Biomedical Applications of Bismuth-Based Compounds and

- Nanoparticles.” Chemical Society Reviews 50: 12037–12069. <https://doi.org/10.1039/D0CS00031K>.
- He, Jian, and Terry M. Tritt. 2017. “Advances in Thermoelectric Materials Research: Looking Back and Moving Forward.” *Science* 357 (6358): eaak9997. <https://doi.org/10.1126/science.aak9997>.
- Hund, Kirsten Lori, Daniele La Porta, Thao Phuong Fabregas Masllovet, Timothy James Laing, and John Richard Drexhage. 2020. *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*. Washington, D.C.: World Bank Group. <http://documents.worldbank.org/curated/en/099052423172525564>.
- Indian Bureau of Mines. 2020. Antimony. *Indian Minerals Yearbook 2020, Part III: Mineral Reviews*. Government of India. https://ibm.gov.in/writereaddata/files/10072021114414Antimony_2020.pdf.
- Indian Bureau of Mines. 2022. Selenium and Tellurium. *Indian Minerals Yearbook 2022, Part III: Mineral Reviews*. Government of India. https://ibm.gov.in/writereaddata/files/171015812565eef12d8fd7dSelenium_Tellurium_2022.pdf.
- Indian Bureau of Mines. 2026. Mineral (Auction) Rules, 2015 (Amended up to 29 January 2026). Ministry of Mines, Government of India. <https://mines.gov.in/admin/download/69d601f1b7d3e1775632881.pdf>.
- Indian Space Research Organisation. 2024. RESPOND Basket 2024. https://www.isro.gov.in/media_isro/pdf/Respond_Basket_2024.pdf.
- Jain, Pradeep Kumar. 2024. “Policy Reforms Initiated for Supply of Critical Minerals in India.” *Mineral Economics* 37 (3): 701–717. <https://doi.org/10.1007/s13563-024-00452-z>.
- Ministry of Mines. 2023. Critical Minerals for India: Report of the Committee on Identification of Critical Minerals. Government of India. <https://mines.gov.in/admin/download/649d4212cceb01688027666.pdf>.
- Ministry of Mines. 2024. Revised Guidelines for Pradhan Mantri Khanij Kshetra Kalyan Yojana (PMKKKY). January 15. Government of India. https://mines.gov.in/admin/storage/ckeditor/2__Revised_PMKKKY_guidelines_15th_Jan_2024_English_1775036164.pdf.
- Ministry of Mines. 2025. “Cabinet Approves ‘National Critical Mineral Mission’ to Build a Resilient Value Chain for Critical Mineral Resources Vital to Green Technologies, with an Outlay of Rs. 34,300 Crore over Seven Years.” Press release, January 29, 2025. <https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2097309®=3&lang=2>.
- National Aeronautics and Space Administration. 2023. “Power: Radioisotope Thermoelectric Generators.” <https://science.nasa.gov/planetary-science/programs/radioisotope-power-systems/power-radioisotope-thermoelectric-generators/>.

- NITI Aayog. 2022. Report of the Inter-Ministerial Committee on Low Carbon Technologies Formed under the India–US Sustainable Growth Pillar of the Strategic Clean Energy Partnership. Government of India. <https://www.niti.gov.in/sites/default/files/2023-02/Report-Committee-on-Low-Carbon-Technologies.pdf>.
- NITI Aayog. 2025. India's Path to Global Leadership: Strategic Imperatives for Viksit Bharat @2047: A Working Paper. Government of India. https://www.niti.gov.in/sites/default/files/2025-04/Working%20Paper%20on%20Strategic%20Imperatives_04042025_NEW.pdf.
- NITI Aayog. 2026. Advancing Circular Economy of Waste Electronic and Electrical Equipment (E-Waste) and Lithium-Ion Batteries in India. Government of India. <https://www.niti.gov.in/node/2108>.
- Press Information Bureau. 2025a. "National Critical Mineral Mission: Powering India's Clean Energy Future." April 9, 2025. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2120525®=3&lang=2>.
- Press Information Bureau. 2025b. "Ministry of Mines Recognizes Two More Centres of Excellence under the National Critical Mineral Mission." October 25, 2025. <https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2182381®=3&lang=2>.
- Press Information Bureau. 2026a. "India Semiconductor Mission 2.0: A Major Push in Budget 2026 towards Semiconductor Self-Reliance." February 7, 2026. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2224839®=3&lang=1>.
- Press Information Bureau. 2026b. "Cabinet Approves Semicon 2.0: Government Delivers on Its Commitment for Long-Term Policy Support to Semiconductors." July 15, 2026. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2284796&lang=1®=3>.
- Rowe, D. M., ed. 2005. *Thermoelectrics Handbook: Macro to Nano*. Boca Raton: CRC Press. <https://doi.org/10.1201/9781420038903>.
- Shetty, Rakshith. 2024. "Assessing the Nature of India's Critical Minerals Vulnerabilities vis-à-vis China." Takshashila Discussion Document 2024-12, Version 1.0. Bengaluru: Takshashila Institution. <https://takshashila.org.in/content/publications/20241217-assessing-nature-of-indias-critical-minerals.html>.
- Snyder, G. Jeffrey, and Eric S. Toberer. 2008. "Complex Thermoelectric Materials." *Nature Materials* 7: 105–114. <https://doi.org/10.1038/nmat2090>.
- START Project. 2026. START Project Newsletter, Issue 8: Final Results and Legacy of Sustainable Thermoelectric Technologies from Mine Waste. May. Zenodo. <https://doi.org/10.5281/zenodo.20382148>.
- Stimson Center. 2025. "China's Germanium and Gallium Export Restrictions: Consequences for the United States." April 2025. <https://www.stimson.org/2025/chinas-germanium-and-gallium-export-restrictions-consequences-for-the-united-states/>.

- Tagotra, Niharika, Nidhi Srivastava, Abhinav Sharma, and T. S. Gowthami. 2024. Critical Minerals for India's Clean Energy Transition. Working Paper. World Resources Institute India. <https://doi.org/10.46830/wriwp.23.00063>.
- United States Geological Survey. 2024. Mineral Commodity Summaries 2024. Washington, D.C.: U.S. Department of the Interior. <https://pubs.usgs.gov/publication/mcs2024>.
- Vining, C. B. 2009. "An Inconvenient Truth about Thermoelectrics." *Nature Materials* 8 (2): 83–85. <https://doi.org/10.1038/nmat2361>.
- Vivekananda International Foundation. 2025. "National Critical Mineral Mission (NCMM): A Strategic Approach to Strengthening India's Mineral Security." February 13, 2025. <https://www.vifindia.org/article/2025/february/13/National-Critical-Mineral-Mission>.
- Zhao, Li-Dong, Shih-Han Lo, Yongsheng Zhang, Hui Sun, Gangjian Tan, Ctirad Uher, C. Wolverton, Vinayak P. Dravid, and Mercouri G. Kanatzidis. 2014. "Ultralow Thermal Conductivity and High Thermoelectric Figure of Merit in SnSe Crystals." *Nature* 508 (7496): 373–377. <https://doi.org/10.1038/nature13184>.
- Zoui, Mohamed Amine, Saïd Bentouba, John G. Stocholm, and Mahmoud Bourouis. 2020. "A Review on Thermoelectric Generators: Progress and Applications." *Energies* 13 (14): 3606. <https://doi.org/10.3390/en13143606>.