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CIRCULARITY IN CLEAN-TECH



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Authors

Dr. Amit Kapoor
Honorary Chairman, Institute for Competitiveness

Sheen Zutshi
Research Manager

Meenakshi Ajith
Development Policy Lead

Darshana Gauratra
Researcher

Mohammad Saad
Researcher

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EXECUTIVE SUMMARY

For two decades the clean energy transition was understood as a problem of generation. It has succeeded by that measure and global energy investment reached USD 3.3 trillion in 2025, of which clean energy accounted for USD 2.2 trillion. But the binding constraint has now shifted to solar modules, batteries and turbines. These are first and foremost, manufactured objects, assembled from refined metals and high-purity materials drawn from concentrated supply chains. The transition is now the fastest-growing manufacturing and materials story in the global economy, and its central vulnerabilities are industrial.

A key vulnerability is the concentration and volatility of the minerals that are processed only in a handful of countries. Lithium prices, having surged eightfold in 2021—22, have since fallen by more than 80%. Additionally, every panel, turbine and battery deployed today is a future end-of-life object, and the global circularity rate has fallen from 9.1% in 2018 to 6.9% in 2025. Recycled volumes are rising, but virgin extraction is rising faster.

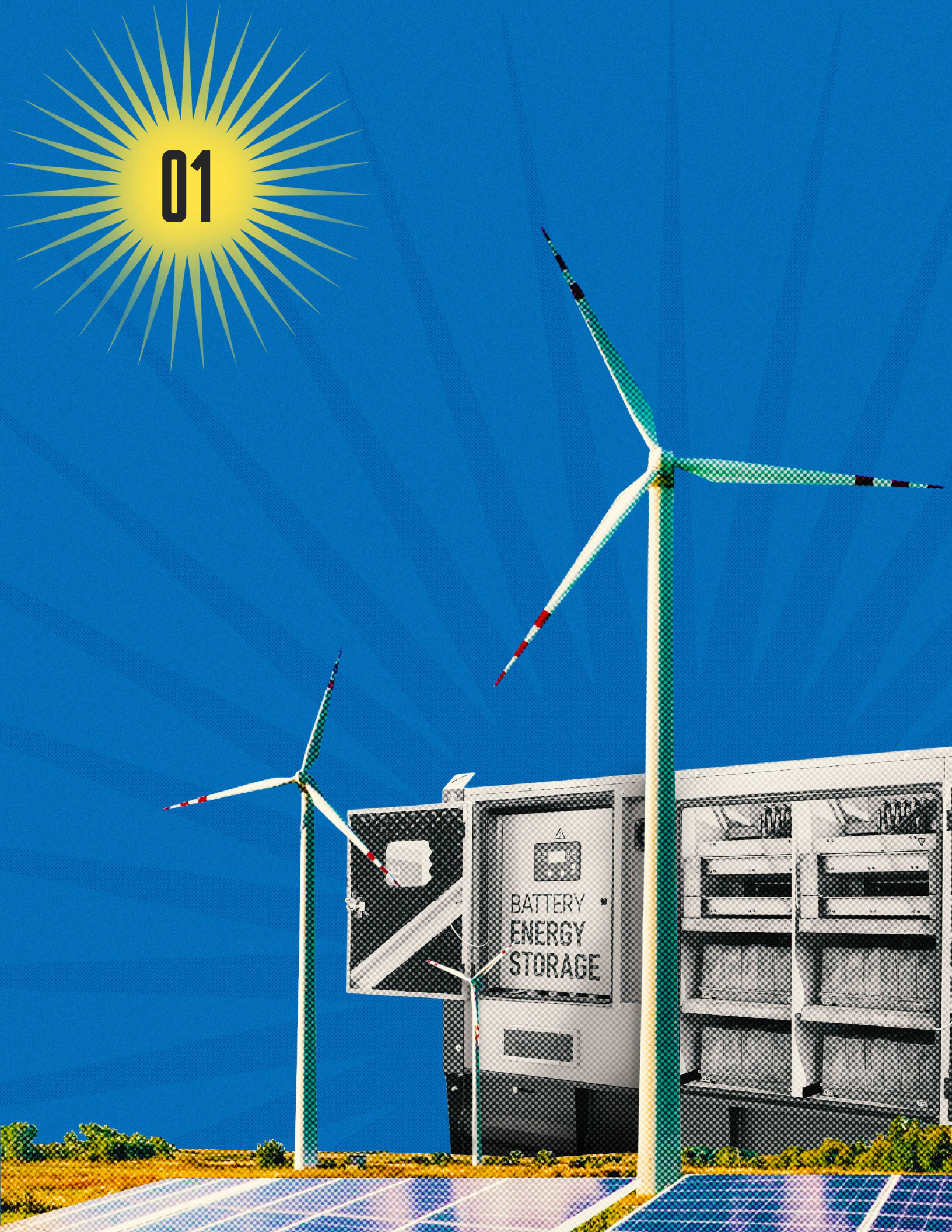
India occupies a unique position in this picture. It is simultaneously one of the world's fastest-growing clean energy markets and an aspiring manufacturing power making foundational industrial choices in real time. Where established industrial economies must retrofit circularity into systems whose designs and supply relationships are already locked in, much of India's clean-tech manufacturing base is still under construction. India therefore retains a design-stage window, the highest-leverage point in the entire circular hierarchy, that others have largely forfeited.

To locate where that leverage sits, the report adapts Michael Porter's value chain framework to sector scale, decomposing solar PV, wind and batteries into discrete stages and mapping India's position at each. The diagnosis is consistent across all three. India has built strength at assembly and integration while remaining dependent on imported critical minerals, processed materials and advanced components at the upstream end, where the highest value is created and captured. Circularity failures turn out to be value chain failures, occurring at specific chokepoints rather than uniformly across the system. A decommissioned module in Rajasthan loses value not because recovery technology is absent but because no take-back infrastructure exists at site. The barriers are architectural: material flows have been designed, implicitly, to be linear.

To build the evidence base for the report's solar assessment, we examine the customs data by component and year to establish what India is buying and from whom. The finding is that an import bill which looks broadly stable in rupee terms conceals physical volumes growing several times faster, and that each successive policy intervention has relocated dependency further upstream rather than resolving it. For wind, the report develops a cohort-based projection of blade waste calibrated to India's installed capacity, tracing when and where decommissioning volumes will arise, state by state and year by year. It shows a sharp and closely dated spike in the mid-2030s, arriving with little warning but concentrated in a handful of states whose peaks fall in different years, which makes the wave more tractable than its scale suggests.

Alongside these, the report looks into the battery demand trajectories and second-life pathways, India's rapidly developed regulatory architecture, and the institutional conditions determining whether recovery becomes a competitive business or remains a compliance cost.

India has built one of the world's largest clean-energy manufacturing bases, but its foundations need to be strengthened further. Building a circular pathway is the way forward to move away from an import-dependent, linear foundation.


01
BATTERY
ENERGY
STORAGE

INTRODUCTION

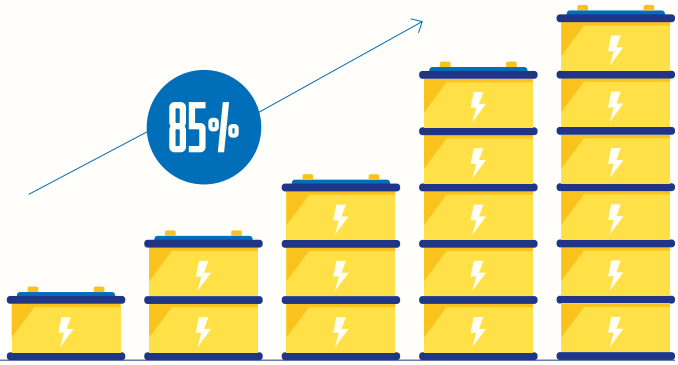
For most of the past two decades, the clean energy transition was understood as a problem of generation. The defining question was one of speed: how quickly solar, wind, and batteries could be deployed, how fast their costs could fall, and whether they could displace fossil fuels at the pace the climate required. By that measure, the transition has succeeded beyond what almost any forecaster predicted. Global energy investment is set to reach a record USD 3.3 trillion in 2025, of which clean energy accounts for USD 2.2 trillion, roughly two-thirds of the total, with solar photovoltaics alone drawing a record USD 450 billion[1]. Clean energy equipment now costs less than half what it did a decade ago. The technologies are no longer emerging and in most major markets they are the default. For instance, today more than one in four cars sold worldwide in 2025 was electric[2]. As a result, the binding constraint on the transition is shifting from how fast clean energy can be deployed to how, and by whom, the hardware that powers it is manufactured, supplied, and ultimately renewed.

This shift matters because it changes the nature of the sustainability question itself. A solar module generates electricity with no emissions and no fuel, and a battery stores it cleanly, but both are, first and foremost, manufactured objects. They are assembled from refined metals, engineered polymers, and high-purity materials drawn from globally dispersed and often concentrated supply chains, and their production carries an industrial and material footprint that the "zero-emissions" label at the point of use entirely obscures. Clean energy technologies are substantially more material-intensive per unit of capacity than the fossil-fuel systems they replace, and the world is now deploying them at a scale that turns that intensity into one of the central industrial facts of the century. Demand for the minerals that underpin these technologies is set to climb steeply: under the IEA's Stated Policies Scenario, lithium demand grows fivefold by 2040, while graphite and nickel demand roughly double and cobalt and rare earth elements rise by 50—60%[3].

The energy sector already accounts for around

85% OF THE RECENT GROWTH

in demand for battery metals such as lithium, nickel, cobalt, and graphite[4].

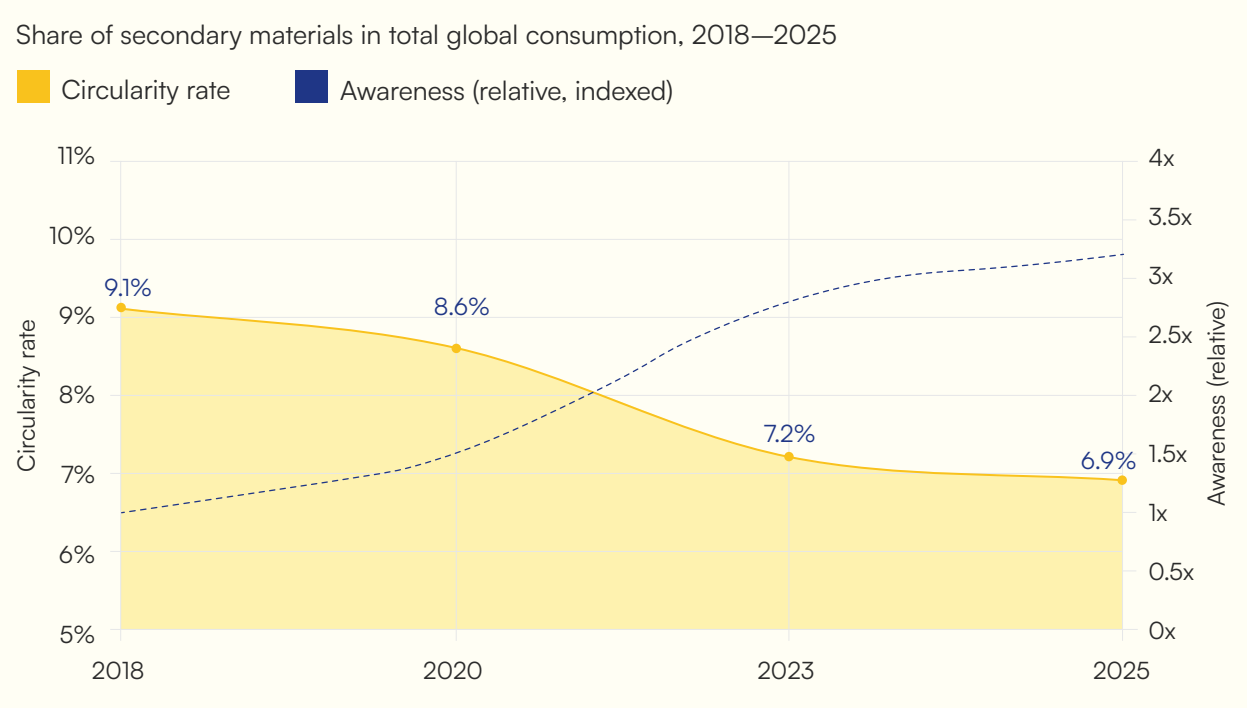


The scale of the build-out behind these numbers is without modern precedent: the lithium-ion battery market alone expanded more than fivefold between 2020 and 2024, to around 1,100 GWh, and is projected to more than triple again by 2030. The transition, in other words, is not only an energy story. It is the fastest-growing manufacturing and materials story in the global economy.

That reframing exposes two structural vulnerabilities that the deployment narrative tended to hide. The first is concentration and volatility. The minerals and components on which clean technologies depend are mined, processed, and assembled in a small number of countries. Efforts to diversify these supply chains are moving too slowly to alter that picture in the near term, and the accompanying price swings are severe: having surged eightfold in 2021—22, lithium prices have since fallen by more than 80%, a collapse that destabilises investment and exposes manufacturers who buy exclusively on primary markets to shocks they cannot control. The second vulnerability is slower moving but equally consequential. Every panel, turbine, and battery deployed today is a future end-of-life object, and the scale of that coming wave is now quantifiable: the number of electric-vehicle batteries reaching the end of their life globally is projected to rise from around 1.2 million in 2030 to roughly 14 million by 2040 and some 50 million by 2050[5], with comparable retirement curves building behind the solar and wind fleets. The world is, through this transition, accumulating an enormous new stock of manufactured material that will, within one or two decades, become either waste to be managed or a resource to be recovered. The prevailing model of how that hardware is made and disposed of remains overwhelmingly linear with a focus on extract, process, manufacture, deploy, discard and replicating that model at the scale the energy transition now demands would build dependence and liability into the foundations of a system meant to deliver security.

Circularity is the response to both vulnerabilities at once, but its strategic value is widely misunderstood and correcting that misunderstanding is the foundation on which this report rests. According to the Circularity Gap Report 2025, only 6.9% of the 106 billion tonnes of materials flowing through the global economy annually come from secondary sources[6]. The volume of recycled material is growing in absolute terms; but virgin material extraction is growing faster.

Figure 1: The global circularity rate is falling - while awareness is rising



Source: Circle Economy Foundation, Circularity Gap Reports 2018—2025 (circularity-gap.world). Awareness index is illustrative, based on report's finding that volume of discussions on circular economy nearly tripled 2018—2023.

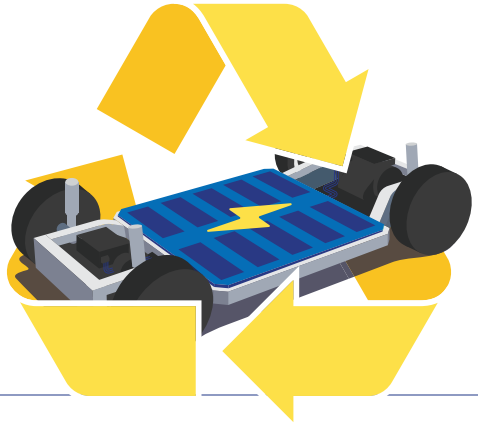
Circularity is too often equated with recycling, with what happens to a product after it fails. Recycling is indeed indispensable: the IEA estimates that scaling it up could reduce the need for new mine development by 25—40% by mid-century, cutting investment requirements by around 30% through 2040, while recycled minerals carry on average 80% lower greenhouse gas emissions than primary materials from mining and the market value of recovered energy-transition minerals is projected to grow fivefold to USD 200 billion by 2050[7]. Yet the deeper lesson of the global evidence is that the highest-leverage circular decisions are made not at the end of a product's life but at its very beginning in the choice of materials, the architecture of the product, and the efficiency of the manufacturing process, often two or three decades before anything is discarded. A further, often overlooked, feature of the present moment reinforces the point: today, almost all of the world's battery-recycling feedstock comes not from spent products but from manufacturing scrap, the offcuts and rejects of production with the balance shifting decisively toward end-of-life material only after 2030 as the installed base ages. The nearest-term circular value, in other words, already sits inside the factory gate, in process losses that can be recovered and fed back into production where design and manufacturing choices determine what is possible. Circularity, properly understood, is therefore a system-level organising principle for industrial production, not a downstream waste-management strategy. It is a way of designing material security, cost stability, and low-carbon competitiveness into a manufacturing base from the outset, rather than attempting to retrofit them once the hardware and its liabilities already exist.

Circularity has also become one of the most dynamic, and most contested, arenas of clean-energy innovation.

As per the IEA, patenting in battery circularity grew by more than

40% A YEAR BETWEEN 2017 AND 2023,

far outpacing almost every other technical field, even as overall energy innovation came to be dominated by battery technologies.



Yet that surge carries a warning for newcomers: rather than dispersing, circular innovation is concentrating in the same economies that already lead in manufacturing, the single largest national share of battery-circularity inventions rose from around 5% in 2013 to nearly 30% a decade later. The window to shape circular industrial systems is therefore open but narrowing on two fronts at once: in the design choices being locked in today, and in an innovation race that rewards incumbents over latecomers.

It is against this backdrop that India occupies an unusual and consequential position. India is simultaneously one of the fastest-growing clean energy markets in the world and an aspiring clean-technology manufacturing power, channelling large-scale industrial policy into building domestic capacity across solar, wind, and batteries. It is also making these foundational industrial choices now, in real time. This is what distinguishes India's circular-economy opportunity from that of most advanced economies.

Where established industrial powers must attempt to introduce circularity into mature, capital-intensive manufacturing systems whose designs, supply relationships, and material flows are already locked in, much of India's clean-tech manufacturing base is still being constructed. The design specifications of its first gigafactories, the architecture of its emerging cell and module lines, and the structure of its component supply chains are not yet fixed. India therefore retains a design-stage window, which is the single most valuable point of intervention in the entire circular hierarchy that others have largely forfeited. The decisions taken in this window will determine, for decades, whether India's clean-energy hardware is built to be recovered or built to be discarded.

That window is valuable in direct proportion to how exposed India's current model is. India has built strength at the assembly and integration end of the clean-tech value chain, but it remains heavily dependent on imported critical minerals, processed materials, and advanced components at the upstream end, where the highest value is created and the greatest leverage held, a dependence concentrated, in most segments, on a single dominant supplier. This is the structural condition that circularity is suited to address, and the case for acting on it is sharpened by a sobering projection: even as its deployment races ahead, India's recycling is expected to cover only around 10% of its critical-mineral needs by 2040 (IEA recycling critical minerals), well below the level its import exposure would warrant. The opportunity cost of that gap is significant, because the energy-security dividend from circularity is greatest in economies that combine limited domestic mineral endowments with high clean-energy deployment and this is a description that fits India closely. For India, then, circularity is not an environmental refinement layered onto industrial strategy. It is industrial strategy: a lever that acts simultaneously on mineral security, production-

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cost stability, export competitiveness, and employment-four dimensions that this report treats not as separate benefits but as systemic consequences of the same underlying choice.

Additionally, India is approaching the leading edge of its own decommissioning curve now, not later. The first generation of wind turbines installed in the early 2000s is already reaching the point of repowering; the leading edge of the solar fleet will begin retiring in scale in the 2030s; and a battery waste stream is rising steeply behind the country's rapid electrification of transport. The infrastructure to capture this material such as collection systems, recovery capacity, traceability, and the regulatory architecture that anchors them takes years to build. Whether India uses the present window to put that infrastructure in place, or stumbles into a crisis once volumes peak, is a decision being made by default in the design and policy choices of the next few years.

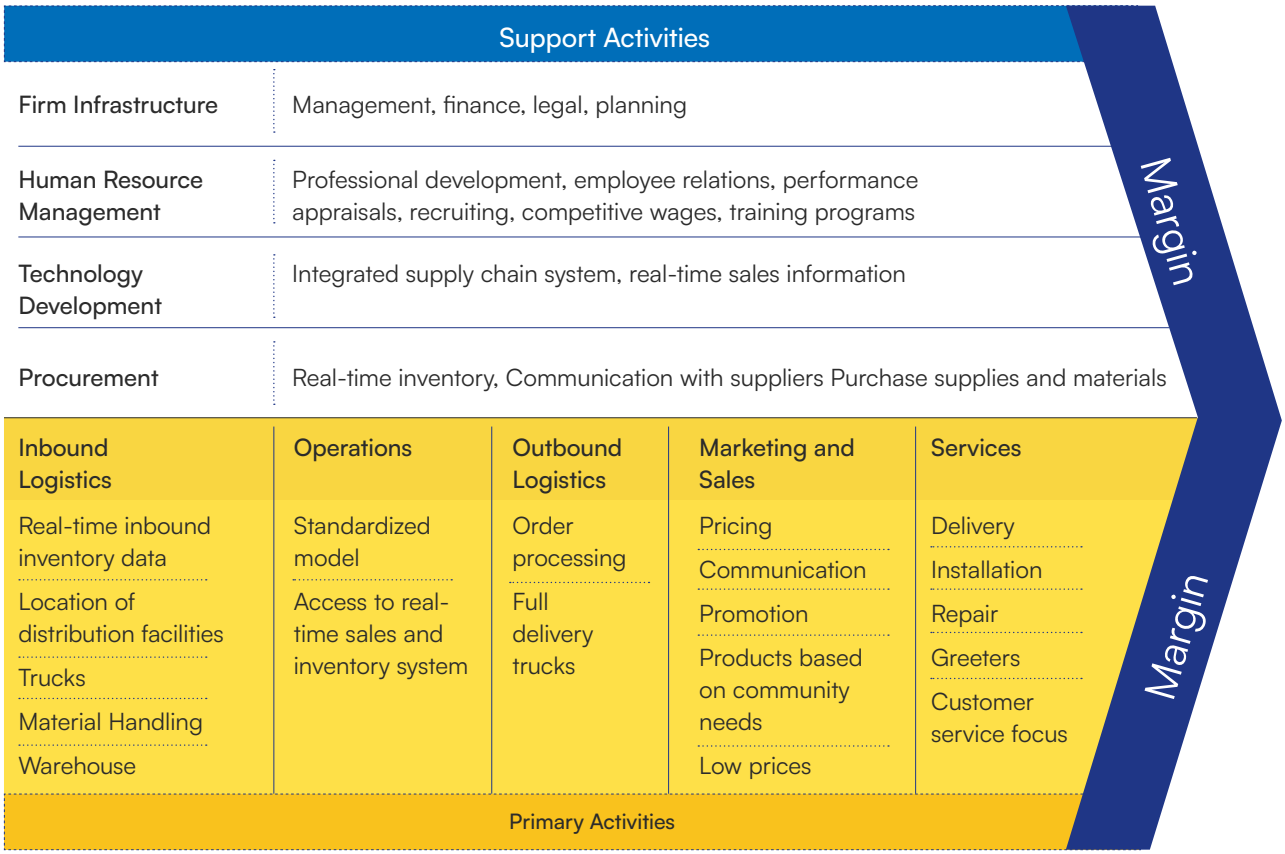
This report examines that decision through the three sectors that sit at the material foundation of India's energy transition: solar PV, wind, and batteries. These are not three sectors chosen from many. They are the technologies that have already reached gigawatt-scale manufacturing in India, that face accumulating and near-term end-of-life waste streams, and that possess the most developed if still nascent policy and regulatory architecture for circularity. India's clean-tech ambitions extend further, to green hydrogen, electrolysers, and high-voltage transmission equipment, but for those frontiers the circular challenge is still largely prospective: the manufacturing base is early-stage, and the material flows are decades away. For solar, wind, and batteries, by contrast, the challenge is immediate. The report proceeds accordingly. It first develops a conceptual framework for circular manufacturing in clean-technology systems, establishing the hierarchy of interventions and the specific levers available at the manufacturing stage. It then surveys the global evidence base across the three sectors what has worked, at what scale, and where the persistent gaps remain before turning, sector by sector, to India: mapping its current position, quantifying the waste waves ahead, and identifying the concrete, actionable interventions that can convert a looming liability into a strategic asset. India has built one of the world's largest clean-energy manufacturing bases on an import-dependent, linear foundation. Circularity is the means by which that foundation is rebuilt from dependence to resilience and the window to do so, while the manufacturing base is open now but still closing soon.



THE VALUE CHAIN LENS

The report draws on Michael Porter's value chain framework which is one of the most enduring and widely applied tools in strategic analysis and adapts it to the specific logic of circular economy at sector scale. Porter introduced the value chain in Competitive Advantage (1985) as a way to decompose a firm's activities into the discrete steps through which value is generated and competitive position is won or lost. His foundational insight was that competitive advantage does not come from a firm as an undifferentiated whole, but from the specific activities within it such as inbound logistics, operations, outbound logistics, marketing and sales, and after-sales service and from the linkages between those activities. A firm that understands where its activities create more value than they cost has found its competitive advantage.

Figure 1.1: Value Chain Analysis



Picture Source: (from Smartsheet)

Though Porter designed the framework for firms, its logic scales naturally. Wherever a complex process can be decomposed into discrete stages and wherever the relationship between those stages determines whether value is created, captured, or destroyed, Porter's architecture applies. Industrial sectors, supply chains, and national economies all have value chains in this sense.

For circular economy, this matters because circularity failures are also value chain failures, and they occur at specific stages rather than across the system uniformly. A decommissioned solar module in Rajasthan or Gujarat loses value not because technologies for material recovery do not exist but because no take-back infrastructure is present at site. In the absence of a reverse logistics supply chain, modules are stockpiled, informally processed or landfilled and thus destroying a resource. **Sector-level value chain analysis is therefore used as a diagnostic tool in this report to ensure recommendations are targeted at actual chokepoints rather than visible symptoms.**

A decommissioned solar module in Rajasthan or Gujarat loses value not because technologies for material recovery do not exist but because no take-back infrastructure is present at site.

The value chain lens is not an academic exercise. It is a tool for accountability for ensuring that recommendations land where the constraint actually is, rather than where it is most visible. Every sector in this report has been analysed through that lens, and in every case, the diagnosis points to the same underlying truth: the barriers to circularity in India are not technical, not financial in the first instance, and not a matter of awareness. They are architectural. The systems through which materials flow have been designed, implicitly or explicitly, to be linear. Redesigning them requires deliberate choices, made now, by people with the authority and the data to make them.


02

STRATEGIC FOUNDATIONS

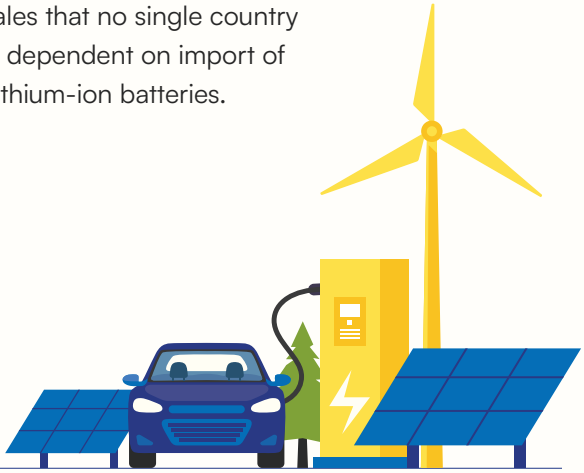
The cleantech sector is at a juncture where the technologies whose purpose is to decarbonise energy systems and reduce environmental pressure are also built from materials whose extraction, processing and disposal can create substantial environmental burdens. The global market for the six key mass-manufactured clean energy solutions including solar PV, wind, electric vehicles, batteries, electrolysers and heat pumps has surpassed $ 700 billion in 2023. This is nearly 4 times its 2015 value and it is projected to reach $ 2 trillion by 2035[8]. However, this expansion is irreversible. India, the European Union, China and US have collectively committed to renewable deployment trajectories that will require hundreds of megatonnes of glass, silicon, lithium, cobalt, nickel, copper and rare earth elements over the next three decades. These technologies need to be deployed. The question for circular economy frameworks is not whether these technologies should be deployed but how the material systems underpinning them can be designed, recovered and recirculated so that the clean energy transition does not merely displace one form of resource dependency with another.

Underneath this material challenge is a structural vulnerability. Critical mineral dependence is as much an economic question as an environmental one. The clean energy transition requires lithium, cobalt, nickel, manganese, graphite, rare earth elements and silicon at scales that no single country can self-supply from primary extraction. India is completely dependent on import of lithium, cobalt and nickel. These minerals are essential for lithium-ion batteries.

India's demand for these minerals is projected to constitute

9% OF GLOBAL DEMAND BY 2050

driven primarily by EVs and solar technologies[9].



Against this backdrop, circular economy principles applied to cleantech are not an environmental add-on to the energy transition. They are a strategic supply chain instrument. The domestic recycling and recovery infrastructure that converts end-of-life cleantech into secondary feedstock for new cleantech, reducing import dependence and geopolitical exposure simultaneously.

India's cleantech expansion makes these structural questions immediate. India Ranks third globally in Renewable Energy Installed Capacity after USA and China. A total of 283.46 GW of capacity from non-fossil fuel sources has been installed in the country. This includes 274.68 GW Renewable Energy (150.26 GW Solar Power, 56.09 GW Wind Power, 11.75 GW Bio Energy, 5.17 GW Small Hydro Power, 51.41 GW

Large Hydro Power) and 8.78 GW Nuclear Power capacity[10]. The 500 GW non-fossil capacity target for 2030 will require an estimated USD 350 billion in investment and could generate over 44 lakh full-time equivalent jobs by 2030 with rooftop solar as the dominant employer. Circular Economy interventions in clean energy supply chains, particularly battery recycling and solar panel circularity, are identified as priority actions for rapidly industrialising middle-income economies. The €25.4 trillion annual Value Gap is substantially driven by structural material linearity in precisely the sectors that are scaling most rapidly[11]. (Circle Economy, 2026) Building the circular infrastructure for cleantech is not a future-state planning exercise for India. The decisions made in the next three years will determine whether India's clean energy buildout becomes a closed-loop industrial system or a mounting waste and import dependency problem.

2.1 THE ELIMINATE CIRCULATE REGENERATE FRAMEWORK

The Ellen MacArthur Foundation developed the Eliminate—Circulate—Regenerate (ECR) framework as the organising logic for systems-level circular transformation. These principles apply to the cleantech sector with particular precision. Eliminate addresses design failures that generate hazardous waste and preclude recovery. Circulate encompasses the second-life, refurbishment and material recovery pathways that keep cleantech materials in productive use. Regenerate connects clean energy deployment to the restoration of the natural systems like land, water and biodiversity that the transition must ultimately serve.

Eliminate

Eliminate in cleantech addresses the upstream design choices that determine whether solar panels, batteries and wind turbine blades can be safely recovered and circulated at end of life or whether they enter the waste streams as toxic and structurally irrecoverable materials. The current solar PV technology that embeds minerals like silicon, silver, aluminium, copper in a laminated structure is optimised for light capture rather than material recovery. Designing modules with more easily separable material assemblies, lead-free solder and standardised encapsulant compositions would make recovery economically viable. However, under the current market structures, module purchasers have no financial incentive to pay a price premium for recyclability, and manufacturers have no obligation to design for it.

The core eliminate intervention for wind turbine blades is design for recycling in blade manufacturing. The structural metal components like the towers and nacelles can be recycled at recovery rates of 80-90 per cent by weight. The composite blades made from glass or carbon fibre-reinforced polymers are structurally resistant to existing recycling routes. Mechanical recycling degrades fibre length and strength, thermal pyrolysis is energy-intensive and produces variable- quality rCF and chemical solvolysis remains at pre-commercial scale. The absence of design for recycling is one of the primary barriers that makes blade end-of-life management economically unviable at current scale. The proliferation of battery chemistries including the LFP, NMC, NCA, LCO and emerging sodium-ion and solid-state configurations has created a fragmented waste stream that complicates sorting, safe handling and recovery. The Battery Waste Management Rules (Amendment) 2024 include provisions for sustainable production practices in line with CPCB guidelines. This is one of the first steps toward embedding design standards in India's battery regulatory framework.

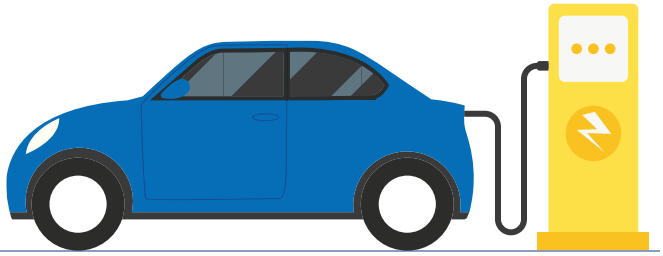
Circulate

Circulate encompasses the full hierarchy of use-extension and material recovery strategies applied across the useful life of solar panels, batteries and wind turbines. The highest value is in preserving by extending first-life use through repair, performance monitoring and operational life extension followed by the second-life repurposing by deploying retired cleantech assets in less demanding applications. Lastly, material-level recycling to recover critical minerals for re-entry into new manufacturing supply chains. Solar panels installed are expected to generate solar module waste of 11,221 kilo tonnes (kt) by 2047[12]. Solar module recycling would substantially reduce India's import burden for critical minerals. By 2047, reduced reliance on virgin materials through recycling could help India avoid 37 million tonnes of CO_2 emissions. However, solar recycling in formal setting is currently unviable for India. The primary barrier is the cost of buying back waste modules, which accounts for nearly two-thirds of total processing costs. Recycling viability depends on EPR certificate trading, tax incentives and R&D investment in improved silicon and silver recovery. These are the same enabling conditions required for any secondary material market to function against a competing virgin material baseline.

EV batteries retain

70–80%

of their energy storage capacity at end of automotive first life.



This makes them suitable for second-life stationary energy storage applications with a battery life extension from 4-8 years to 10-15 years[13]. A potential 49.2 GWh market for second-life batteries in India from retired EV batteries between 2022 and 2030 can be expected as battery demand is projected to increase more than 40-fold by 2050[14]. Indian startups like Nunam, Lohum, BatX Energies, Attero Recycling are actively deploying second-life applications. Attero targeted 15,000 tonnes of lithium-ion battery recycling in FY 2024-25. The BWMR 2025 amendment formally recognises second-life battery repurposing as a valid pathway before end-of-life recycling with registered refurbishers eligible to generate EPR credits. India's wind fleet which has an installed capacity of more than 56GW includes a growing cohort of first-generation turbines approaching 20—25-year design lives. The replacement of older, smaller turbines with fewer, larger and high-efficiency turbines on the same site would be the highest-value circulation strategy. It would retain site permissions and grid connections while recovering structural steel for secondary steel markets. Material-level recovery for composite blades remains constrained by the technical barriers. However, near-term scalable options can divert waste from landfill as advanced chemical recycling methods scale towards commercialisation.

Regenerate

Regeneration in cleantech circularity connects the energy transition to the restoration of natural systems in two ways. First, the displacement of fossil fuel extraction and combustion by renewable energy which directly reduces the land degradation water contamination and atmospheric pollution associated with coal mining, oil drilling and gas processing. They have been one of the most severe drivers of natural capital loss in India and globally. Second, the circular management of cleantech waste prevents the secondary

environmental impacts of landfilled or informally dismantled solar panels, batteries and wind turbines. Otherwise, these factors would degrade the ecological resilience that regenerative development depends on.

Agrivoltaic systems, the co-deployment of solar panels above agricultural land, reduces soil moisture evaporation, moderate temperature and can improve crop yields under certain conditions. These principles have the capacity to generate energy while simultaneously restoring productive land function. In India's semi-arid regions Agrivoltaic yields can be 14—23 per cent higher per unit land area than either solar-only or agriculture-only deployments[15]. The PM-KUSUM scheme deploys solar pumps and grid-connected solar on agricultural land and it provides a policy platform for scaling agrivoltaic deployment across India's 140 million hectares of farmland.

2.2 ADAPTING ECR TO INDIA'S CLEANTECH CONDITIONS

India's cleantech sector presents a distinctive structural configuration that defines how ECR principles can translate into actionable strategy. The Circularity Gap Report 2026 identifies critical mineral supply chains and renewable energy end-of-life management as priority intervention areas for middle-income economies with rapidly scaling clean technology deployment.

The 500 GW pipeline as a double-edged asset

India's commitment to 500 GW of non-fossil capacity and ahead-of-target achievements in the have created both and urgency and an opportunity for cleantech circularity. The cumulative solar waste from capacity deployed by 2030 alone will reach 600 kilotonnes by 2030 and 19,000 kilotonnes by 2050[16]. This is the urgency. Five states including Rajasthan, Gujarat, Karnataka, Andhra Pradesh and Tamil Nadu will generate the majority of this waste. This geographic concentration would enable hub-based recycling infrastructure at a practical scale. The 500GW of deployed solar and wind also represents a massive urban mine of critical minerals and high grade materials that could supply a significant fraction of India's clean energy manufacturing input demand from domestic secondary sources rather than imported primary material. However, it would require reverse logistics and processing infrastructure. This is the opportunity.

Import dependence on core critical minerals

India's clean energy industry's ambitions are structurally exposed. There is a 100 per cent import dependence on lithium, cobalt and nickel. This translates to every EV and every grid-scale storage project constitutes a critical supply chain vulnerability. China controls majority of the processing and supply of all these minerals. India's demand for critical minerals is expected to more than double by 2030. The domestic mining projects will take more than a decade to become operational[17]. Against this, domestic recycling is more than an environment measure ,is a strategic supply chain intervention. Circular economy principles including reducing, substituting and recovering critical raw minerals represents an emerging solution to reducing import dependency that complements rather than replacing the primary sourcing diplomacy[18].

The formal-informal recycling gap in waste streams

India's e-waste and battery recycling economy includes a large informal sector that dismantles solar panels, batteries and electronic components. The processing is done without a safety infrastructure which

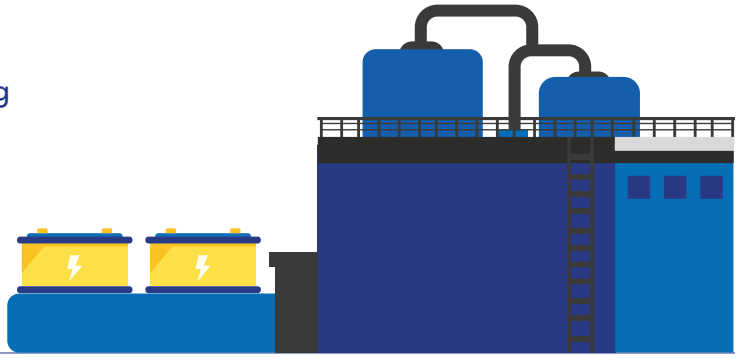
can create occupational health risks and material contamination that degrades the quality of recovered materials. India currently recycles less than 3 per cent of end-of-life lithium-ion batteries formally. This implies that more than 97 per cent of end-of-life lithium-ion batteries enters the informal channels or accumulates in storage awaiting future regulation[19]. The EU-India Clean Energy and Climate Partnership's battery circularity report recommends a hub-and-spoke model for India. Under this model, local facilities would handle collection, safe storage and black mass production, and would connect to centralised hydrometallurgical refining plants. Such an architecture would draw the informal sector into the formal chain while maintaining geographic accessibility and cost viability[20].

The manufacturing ecosystem challenge

The Advanced Chemistry Cell PLI scheme was launched in 2021 targeting

50 GWH

of domestic battery manufacturing capacity by 2025.



As of October 2025, only 1.4 GWh (2.8 per cent of target) has been commissioned and entirely by OLA Electric[21]. The underperformance of this scheme reflects a structural diagnostic. India lacks a mature cell manufacturing ecosystem including critical mineral refining, cell component production and qualified technical workforce. Therefore, the battery industry is almost entirely dependent on China for cell chemistry, equipment and specialist installation capabilities. The circular economy strategy for batteries in India must therefore operate across two timescales simultaneously. First, the life and recovery of the batteries India imports and deploys now needs to be maximised. Second, the domestic manufacturing and materials ecosystem that enables India to produce, recycle and remanufacture batteries from domestically processed minerals need to be build.

2.3 ALIGNMENT WITH INDIAN REGULATORY AND POLICY FRAMEWORKS

India's regulatory architecture for cleantech circularity has undergone rapid and consequential development in the last 5 years. It has advanced from a framework that treated solar panels and batteries primarily as production assets to one that recognises them as material resources that require end-of-life governance. The regulatory architecture is substantive now. However, the implementation, enforcement and the commercial viability of circular pathways remain structurally dependent on further action.

01 Battery Waste Management Rules

The Battery Waste Management Rules established India's first comprehensive Extended Producer Responsibility framework for all battery categories ranging from portable, automotive to industrial and electric vehicles in 2022. The Rules prohibit landfilling or incineration of collected batteries and mandate

the collection and recycling targets that escalate annually and has established a centralised CPCB EPR portal for producer and recycler registration and certificate exchange. For EV batteries, the Rules established one of the most ambitious frameworks among emerging economies. Material recovery targets for lithium-ion batteries increase from 70 per cent in FY 2024—25 to 80 per cent in FY 2025—26 and 90 per cent from FY 2026—27 onwards. It is also required by producers to incorporate domestically recycled materials into new batteries beginning in FY 2027-28. The minimum recycled-content obligations have also progressively risen from 5 per cent to 20 per cent by 2030.

The Rules were amended in 2025 which added mandates for sustainable production practices. The BWMR 2025 amendments further formalise second-life battery repurposing as a valid compliance pathway. There is explicit recognition of stationary energy storage applications as a use category before mandatory end-of-life recycling. 58.26 lakh tonnes of battery waste have been recycled, and 4,022 producers and 487 recyclers were registered under the framework (PIB, 2025). The EPR mechanism has encouraged the formalisation of informal sector to generate revenues from exchange of EPR certificates with producers, in addition to the revenue generated from sale of recycled materials. The Rules are a step towards representing meaningful early-stage formalisation of a market that was entirely informal before 2022.

Complementing the NCMM, the Union Cabinet in September 2025 approved a Rs 1,500 crore Incentive Scheme to Promote Critical Mineral Recycling from FY 2025-26 to 2030-31.

02 National Critical Minerals Mission (NCMM) and Recycling Incentive Scheme

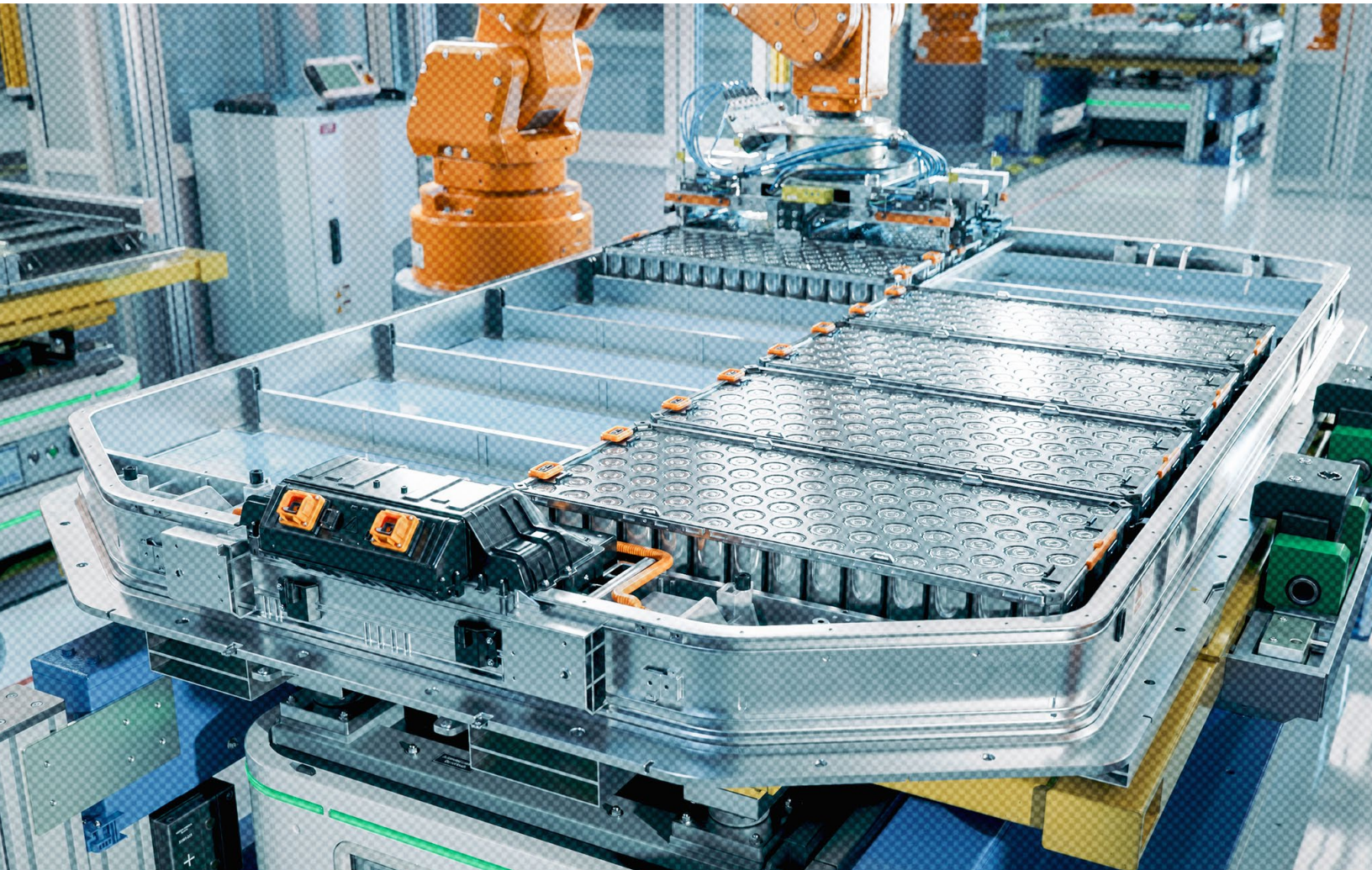
The National Critical Minerals Mission (NCMM) was approved by the Union Cabinet in 2025 with a funding allocation of INR 16,300 crore for FY 2024-25 to 2030-31. This is the most significant policy instrument in connecting cleantech circularity to strategic supply chain sovereignty. The NCMM covers the full critical mineral value chain from exploration, auction and mine operationalisation through to acquisition of foreign assets and recovery from end-of-life products. The Ministry of Mines in November 2023 identified 30 critical minerals (PIB, 2025). The Mission's inclusion of secondary recovery from e-waste, LIB scrap and other waste streams as an explicit mandate operationalises the circularity principle that domestic recycling is a supply chain instrument for securing critical minerals and not merely a waste management activity. This is a critical shift in policy thinking.

Complementing the NCMM, the Union Cabinet in September 2025 approved a Rs 1,500 crore Incentive Scheme to Promote Critical Mineral Recycling from FY 2025-26 to 2030-31. The scheme supports the recovery of critical minerals from e-waste, lithium-ion batteries, manufacturing scrap and other end-of-life products. It is the first direct financial incentive for critical mineral secondary production in India. The Ministry of Mines issued guidelines in November 2025 for pilot projects focused on extracting critical minerals from overburden, tailings, mine waste and other secondary resource streams. Thus, reinforcing the role of circularity in India's critical mineral strategy.

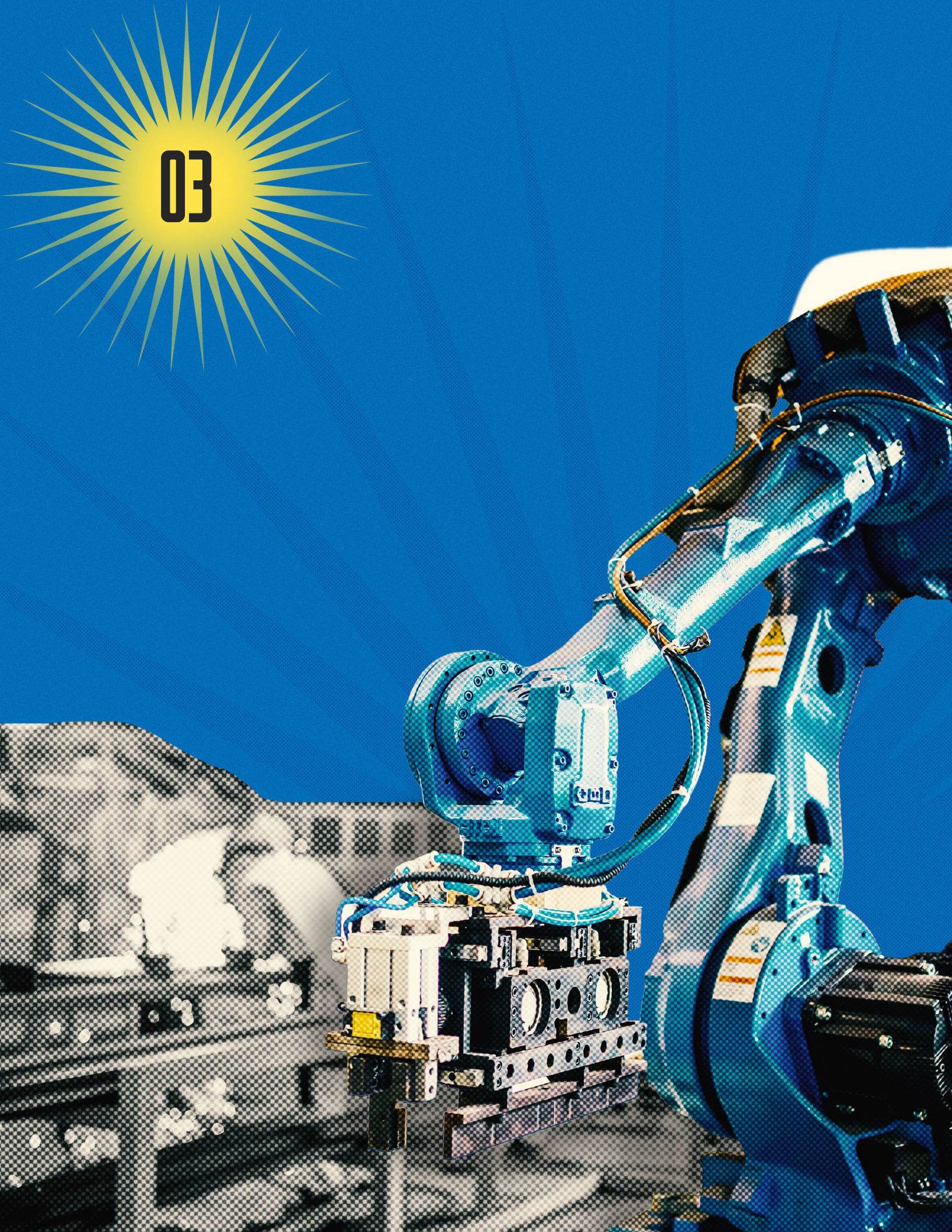
03 PLI Schemes for Solar PV and Battery Manufacturing

India's Production Linked Incentive (PLI) framework covers two cleantech sectors which are strategically important for circular economy development. The PLI scheme for High Efficiency Solar PV Modules has allocated more than ₹24,000 crore to support domestic manufacturing across the solar value chain. Thus, reducing the import dependence while creating the foundations for future incorporation of recovered silicon, glass, aluminium, copper and silver from end-of-life modules. Similarly, the Advanced Chemistry Cell (ACC) Battery PLI scheme has an outlay of ₹18,100 crore and a manufacturing target of 50 GWh. It seeks to establish domestic battery manufacturing capacity that can ultimately absorb recycled lithium, nickel, cobalt, graphite and other critical materials recovered from end-of-life batteries.

ACC manufacturing deployment has progressed more slowly than initially envisaged, with only a small share of planned capacity operational as of early 2026 (IEEFA, JMK, 2026). Thus, reflecting persistent constraints in critical mineral processing, cell-component manufacturing and upstream supply chains. The significance of the PLI framework extends beyond manufacturing alone. The circular economy relevance of the framework is primarily upstream. A domestic manufacturing base creates the infrastructure and commercial incentives for co-located recovery of end-of-life materials, closing the loop between manufacturing scrap, deployed assets and secondary feedstock. Without domestic manufacturing, the economic case for domestic recycling is weakened. Therefore, the underperformance of the ACC PLI has circular economy implications that extend to the viability of the battery recycling ecosystem it was intended to anchor. The PLI schemes address the demand side of circularity while the EPR, Battery Waste Management Rules and recycling incentives address the supply side. Together, they create holistic conditions for a domestic secondary materials market.



03

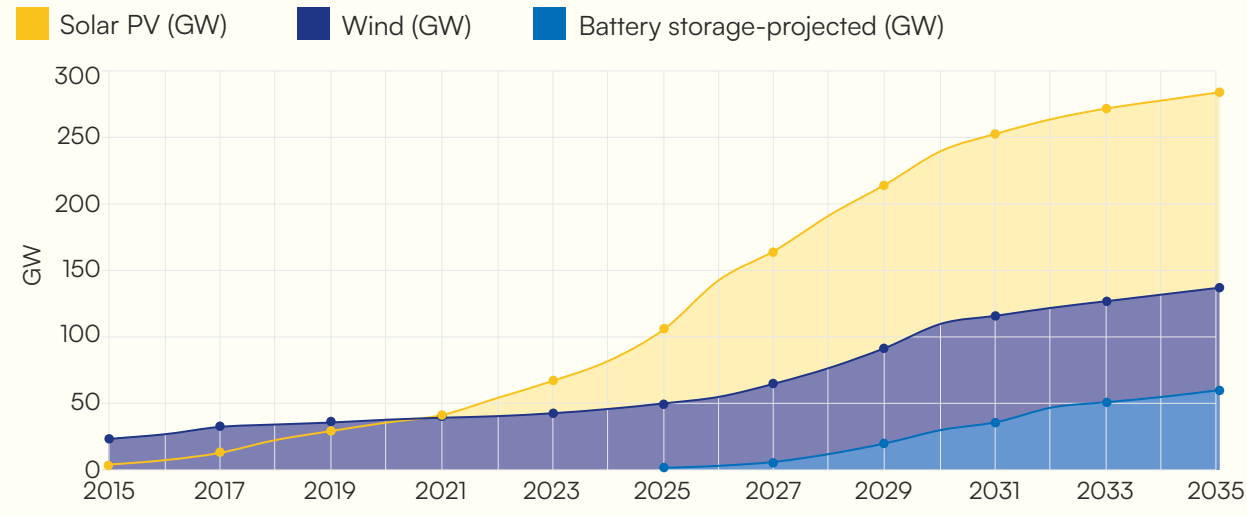


CIRCULAR INTERVENTIONS: GLOBAL LESSONS AND PATHWAYS FOR INDIA

India's clean energy transition is entering a fundamentally new phase, defined not just by deployment, but by industrial scale, material intensity, and manufacturing depth. Over the past decade, the country has emerged as one of the fastest-growing renewable energy markets globally, with total renewable capacity crossing 250 GW in 2025, driven largely by solar and wind expansion. Solar capacity alone has reached over 143 GW, while wind has surpassed 55 GW, reflecting a rapid shift in the energy mix[22]. This expansion is set to accelerate further. Recent projections indicate that India's solar capacity could quadruple and wind capacity could triple by 2035, alongside a massive scale-up in battery storage from negligible levels today to 80 GW[23]. This scale also alters the nature of the energy transition: **from a question of how quickly clean technologies can be deployed, to how sustainably they can be manufactured, supplied, and renewed over time.**

At this scale, clean energy systems are no longer just infrastructure, but they are material-intensive industrial systems. India's renewable energy capacity has expanded from approximately 35 GW in 2015 to over 250 GW by February 2026, with solar alone growing from under 4 GW to over 143 GW marking a thirty-eightfold increase in eleven years[24]. The curve below traces this shift and projects where policy targets point by 2035.

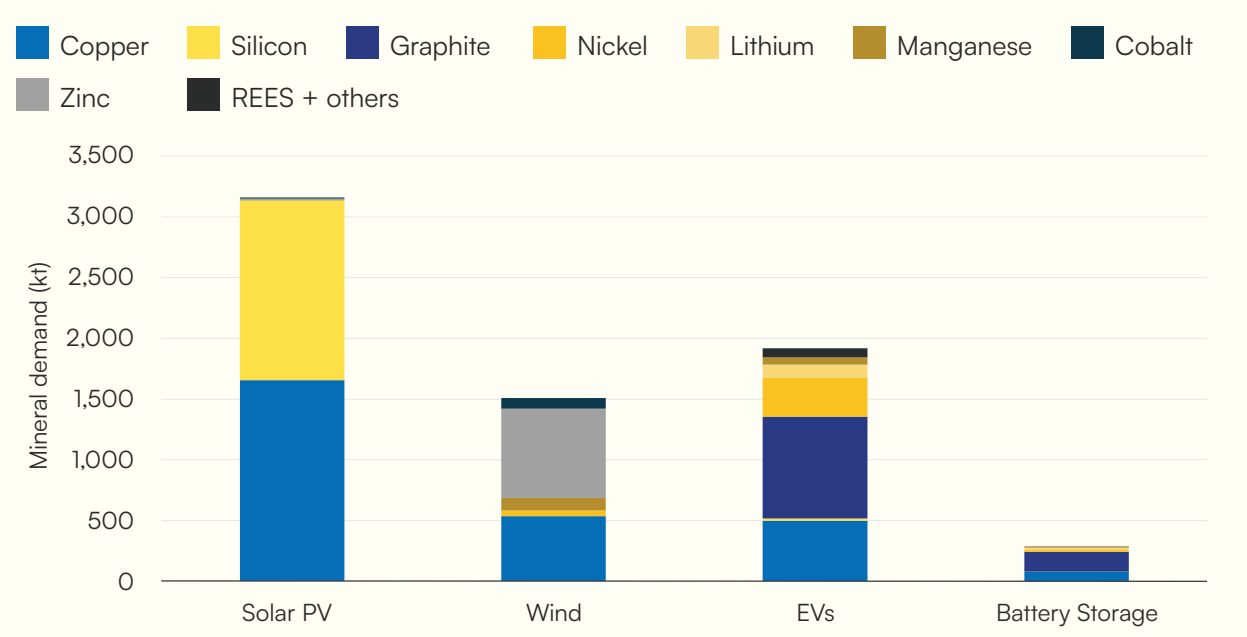
Figure 3.1: India's Energy Transition in Numbers: From Base to 2035 Projections



Sources: MNRE Year-wise Achievements (solar & wind cumulative actuals); battery storage projections from CEA National Electricity Plan 2023 (47.2 GW by 2032) and IEA/IECC modelling; 2033-2035 extrapolated from policy trajectory. Actuals through Feb 2026.

Each of these technologies also have significant requirements in terms of critical minerals. The below chart illustrates what this transition actually requires in physical terms, using IEA baseline data for 2024. Each clean technology has a distinct mineral fingerprint. Solar PV runs largely on copper and silicon and these are materials with well-established supply chains. EVs and battery storage are more complex, drawing on lithium, graphite, nickel, and cobalt, many of which are mined in a small number of countries and carry significant supply risk. Wind power's largest material requirement is in fact zinc, which is used to galvanise steel towers rather than the rare earth elements that typically dominates. As India scales each of these technologies toward its 2030 targets, the volumes involved grow proportionally. **Managing where these materials come from, and what happens to them at end of life, sits at the heart of the circular economy challenge.**

Figure 3.2: Mineral demand by clean energy technology, 2024 baseline (kt)



Source: IEA Critical Minerals Data Explorer, 2024 baseline demand (kt). Stated Policies Scenario. REES = rare earth elements (neodymium, dysprosium, praseodymium, terbium) + chromium + boron for wind; vanadium excluded (near-zero 2024).

For India, this raises a critical structural challenge: high dependence on imported materials and components, particularly for upstream solar manufacturing (cells, wafers, polysilicon), battery minerals, and advanced wind components[25]. As India simultaneously pushes for domestic manufacturing through initiatives such as the Production Linked Incentive (PLI) schemes, the focus is shifting toward building resilient, competitive, and self-reliant supply chains. However, replicating a linear, resource-intensive manufacturing model at this scale risks creating new vulnerabilities like exposure to volatile global mineral markets, rising production costs, and embedded carbon emissions in supply chains.

This is where circularity becomes central not as a waste-management strategy, but as a core industrial strategy. Clean energy systems can be organised around two fundamentally different logics. In the linear model, value flows in one direction from extraction through to waste. In the circular model, feedback loops at manufacturing, deployment, and end-of-life redirect materials back into the chain, reducing dependence on virgin extraction at every cycle.

Figure 3.3: From Linear to Circular: How Materials Flow Differently

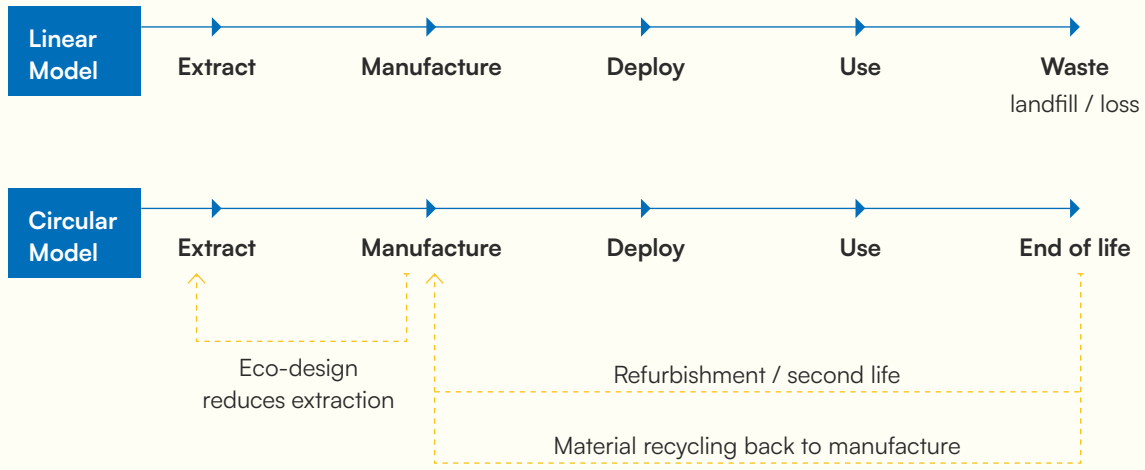
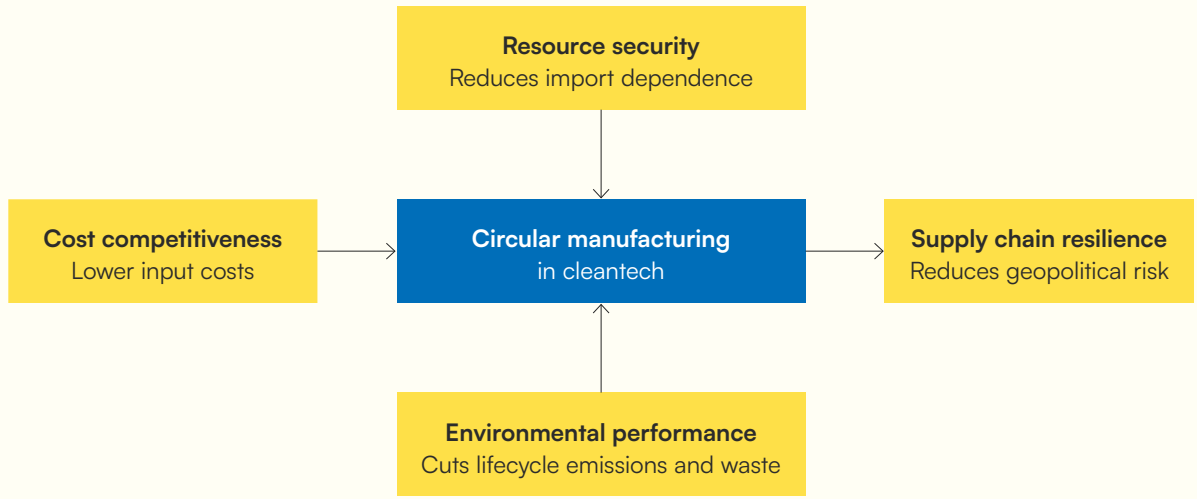


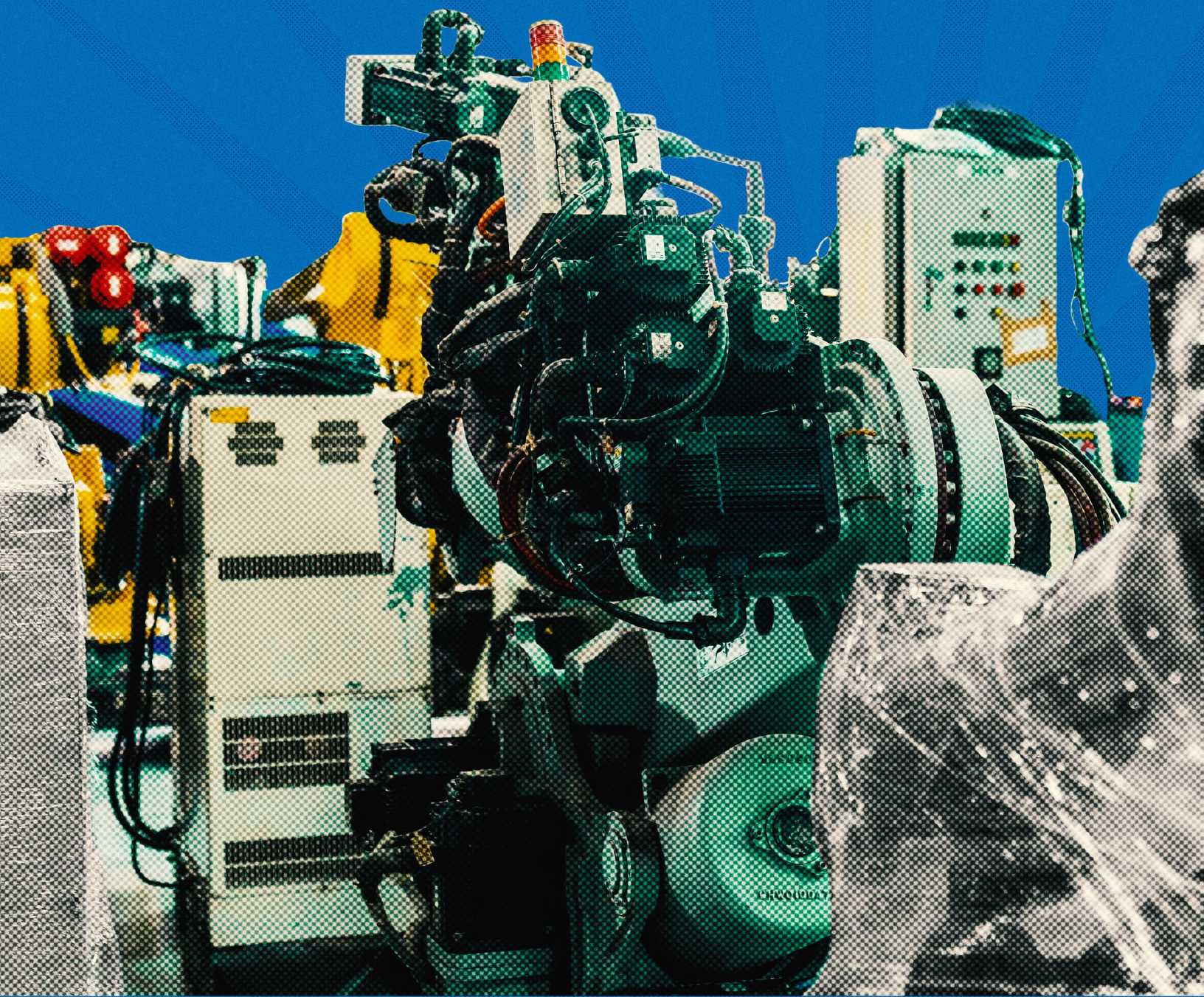
Figure 3.4: Circular manufacturing in cleantech directly addresses four systemic risks



The waste wave facing India in the future cannot be ignored. India's early solar installations will begin reaching end-of-life at scale after 2035, battery waste is expected to rise sharply with EV adoption, and wind turbine blades will create a new composite waste stream. Without circular systems embedded early, India risks locking in a linear "build—discard—replace" pathway at massive scale. Crucially, global experience shows that the most effective circular outcomes are not achieved at end-of-life but are designed into manufacturing systems from the outset through material choices, product architecture, process efficiency, and value-chain integration.

This chapter therefore focuses specifically on circular interventions at the manufacturing stage and across the value chain moving beyond end-of-life waste management to examine how India can embed circularity into the foundation of its clean-tech industrial transition.

04



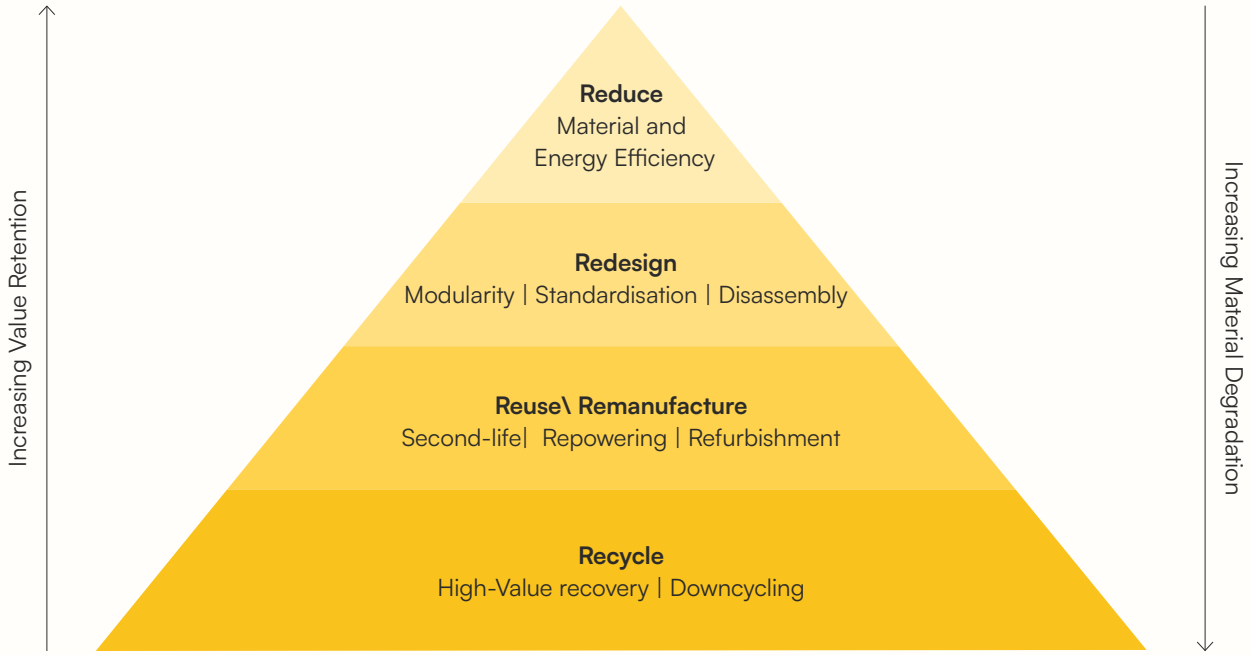
CONCEPTUAL FRAMEWORK: CIRCULAR MANUFACTURING

The sustainability of clean energy systems is increasingly determined not by operational emissions alone, but by the material intensity and value-chain configurations that underpin them. In this context, circularity is a system-level organising principle for industrial production, not a downstream waste-management strategy. This section develops a conceptual framework for circular manufacturing in cleantech, grounded in global evidence and adapted to the specific characteristics of energy technologies such as long lifetimes, complex material compositions, and rapidly scaling demand.

4.1 A HIERARCHY OF CIRCULAR INTERVENTIONS IN CLEANTECH

Circularity in industrial systems is often conceptualised as a hierarchy of interventions, prioritising those that preserve value at higher levels over those that recover value after degradation[26]. In the context of cleantech manufacturing, this hierarchy acquires particular importance due to the high material intensity and strategic significance of critical minerals.

Figure 4.1: **Circular hierarchy of interventions in clean technology manufacturing. Strategies that reduce material use and enable redesign retain the highest value, while recycling represents the lowest level of value retention despite its importance.**



At the highest level is material and energy reduction, which directly addresses the scale of resource demand. Clean energy technologies are significantly more material-intensive per unit of capacity than conventional fossil-based systems. The IEA estimates that demand for critical minerals such as lithium, cobalt, nickel, and rare earth elements could increase several-fold by 2040 under net-zero pathways[27]. In this context, reducing material intensity through improved manufacturing yields, material substitution, and process optimisation represents the most effective form of circularity. For example, advances in photovoltaic manufacturing have focused on reducing silver consumption in cell metallisation, while battery manufacturing is increasingly targeting lower energy intensity through process innovation, including solvent recovery and dry electrode technologies[28]

The second level involves redesigning products and manufacturing systems to enable circular flows. Design decisions relating to material selection, product architecture, and assembly methods have long-term implications for circularity, particularly given the 20—30-year lifetimes typical of energy technologies. In batteries, the lack of standardisation in pack design has emerged as a major barrier to disassembly, diagnostics, and recycling[29]. Similarly, the lamination structures used in conventional crystalline silicon PV modules complicate material separation, limiting the recovery of high-value materials such as silicon and silver[30]. Design for modularity, disassembly, and standardisation therefore represents a critical enabler of downstream circular strategies.

A third level of intervention focuses on extending product lifetimes through reuse, refurbishment, and remanufacturing. These strategies preserve the functional value of products and the embedded energy and materials they contain. In the battery sector, second-life applications where electric vehicle batteries are repurposed for stationary energy storage have emerged as a promising pathway to extend asset lifetimes and defer recycling[31]. In wind energy, repowering strategies allow for the selective replacement of components while retaining usable infrastructure. However, the viability of these approaches depends on reliable diagnostics, standardised testing protocols, and clear liability frameworks and these are areas where institutional development remains uneven.

At the lowest level of the hierarchy is recycling, which, while essential, typically involves some degree of value loss. The distinction between high-value recycling and downcycling is particularly important in cleantech systems. High-value recycling aims to recover materials in forms suitable for direct reintegration into manufacturing for example, the recovery of cathode materials in batteries while downcycling often results in lower-grade outputs with limited applicability. The IEA suggests that recycling could reduce primary mineral demand by up to 10—30% by 2040 under certain scenarios, but achieving this potential depends on scaling high-recovery, high-purity processes[32]. In solar PV, the economic viability of recycling hinges on the recovery of silver and high-purity silicon, while in wind energy, composite blade materials remain a significant challenge due to limited high-value recovery pathways[33].

4.2 OPERATIONALISING CIRCULARITY IN MANUFACTURING SYSTEMS

While the hierarchy provides a conceptual structure, circularity is realised through specific interventions at the manufacturing stage. These interventions operate across the full manufacturing lifecycle from product design and material sourcing through process engineering and end-of-life value-chain integration.

A central lever is design for circularity, which integrates considerations of disassembly, repairability, and material recovery into product development. Evidence from the European Commission suggests that up to 80% of a product's environmental impact is determined at the design stage, underscoring the importance of early intervention[34]. In cleantech manufacturing, this includes reducing reliance on scarce or hazardous materials, enabling modular replacement of components, and aligning product configurations with recycling capabilities.

Process efficiency and yield improvement represent another critical pathway. Manufacturing processes in clean energy technologies often generate significant material losses. In photovoltaic manufacturing, silicon losses during wafer slicing have historically been substantial, although ongoing innovation is reducing these inefficiencies. In battery manufacturing, particularly during early-stage gigafactory ramp-up, scrap rates can be significant, reflecting the complexity of production processes[35]. Improving yield not only reduces material demand but also enhances economic competitiveness.

The integration of secondary materials into manufacturing systems is a further dimension of circularity. The use of recycled inputs can reduce dependence on virgin materials and lower lifecycle emissions. However, this requires reliable supply chains for high-quality recovered materials, as well as standards to ensure performance consistency. In batteries, recycled nickel, cobalt, and lithium have the potential to significantly offset primary demand, while in solar manufacturing, recycled aluminium and glass are already widely used. A particularly immediate and economically viable opportunity lies in closed-loop recovery of manufacturing scrap. Unlike end-of-life waste, manufacturing scrap is typically homogeneous and uncontaminated, making it well-suited for reintegration into production processes[36]. This is especially relevant for battery electrode materials and silicon waste in PV manufacturing.

Digitalisation also plays an increasingly important role in enabling circularity. Digital traceability systems, including product passports, can address information asymmetries by providing data on material composition, manufacturing history, and performance over time. The emergence of battery passports in regulatory frameworks such as the EU Battery Regulation reflects a broader shift towards data-driven circularity.

Finally, **industrial symbiosis** offers a system-level approach to resource efficiency, linking material and energy flows across industries. By integrating cleantech manufacturing with adjacent industrial processes such as chemicals, metals, and construction, waste streams can be transformed into valuable inputs, reducing overall resource consumption[37].

4.3 GLOBAL EVIDENCE: CIRCULAR INTERVENTIONS IN CLEANTECH MANUFACTURING

Before designing India-specific circular economy strategies for cleantech manufacturing, it is essential to survey what the global evidence base demonstrates in terms of which interventions work, at what scale, under what conditions, and where the persistent gaps remain. The three most advanced sectors batteries, solar PV, and wind offer distinct but some shared lessons.

Global evidence: circular interventions in cleantech manufacturing

Dimension	**Batteries** Most mature circular ecosystem	**Solar PV** Manufacturing waste overlooked	**Wind** Blade circularity as bottleneck
Circular maturity	High - most developed recycling infrastructure globally	Medium - end-of-life infrastructure emerging; manufacturing waste underutilised	Low-medium - 85—90% of turbine recyclable; blade remains unsolved
Scale of opportunity	• Market projected to grow from USD 16.23bn (2024) to USD 56.87bn by 2033 • Recycling could meet 20—30% of Li, Ni, Co demand by 2050	• 78 Mt of raw materials and components recoverable globally by 2050 • Recoverable material value exceeding USD 15bn by 2050 • EOL wave: 0.2 Mt waste (2021) → 60-80 Mt by 2050 (IRENA)	• Decommissioned blade material in China alone: 7.7—23.1 Mt by 2050 • Repowering identified by IRENA as critical lever for tripling RE capacity by 2030
Key interventions	• Direct cathode recycling: preserves crystal structure; costs €0.71/kg (LFP) and €1.17/kg (NMC) below virgin prices • Hydrometallurgical recycling: 50% energy reduction vs virgin extraction (China) • AI-based sorting and direct recycling (US): 95% resource recovery efficiency • Closed-loop manufacturing scrap recovery: homogeneous, uncontaminated feedstock	• Kerf loss reduction: ROSI Solar recycles high-purity silicon from diamond-wire saw waste • US manufacturers achieving 85% silicon waste recycling; 90%+ silver and silicon recovery • Chemical and water-jet delamination (QUASAR/CABRISS): 70—90% recovery of silicon, glass, metals • Silver substitution: copper metallisation reducing critical material dependency	• Mechanical recycling: most cost-efficient but lowest fibre quality • Cement co-processing: most commercially viable ($27.57/tonne profit) but downcycling • Solvolysis/pyrolysis: highest fibre quality but TRL 4—6; not yet at scale • Thermoplastic blades (NREL/Elium resin): comparable performance; no energy-intensive curing • PECAN resin (plant-based): enables full fibre and hardener recovery

Dimension	**Batteries** Most mature circular ecosystem	**Solar PV** Manufacturing waste overlooked	**Wind** Blade circularity as bottleneck
Leading policy instruments	• EU Battery Regulation (2023/1542): minimum recycled content (16% Co, 6% Li, 6% Ni from 2031); recovery targets 90% Co/Ni/Cu, 50% Li • Battery passports mandated from Feb 2027 for EV/industrial batteries >2 kWh • Portable battery collection: 63% by 2027, 73% by 2030 • China EPR under 14th Five-Year Plan: strict targets; 40% recycling rate achieved	• EU WEEE Directive: 85% collection, 80% recycling rate for PV modules in Europe • EU Horizon funding: QUASAR, CABRISS closed-loop demonstration projects • No equivalent global mandate; recycling rates outside Europe lag significantly	• No global end-of-life regulation for blades • IRENA: repowering as near-term lever; streamlined permitting required • Spain evidence: life extension and repowering consistently outperform decommissioning economically • Policy gap: recycled content mandates, procurement standards, carbon pricing all absent
Current recycling rates	• China: ~40% battery recycling rate; 90% material recovery • US: ~35% recycling rate; 95% resource recovery • Manufacturing scrap: two-thirds of recycling feedstock today; shifts post-2030 to EOL batteries	• Global: 22—49% by 2030 depending on policy scenario (IEA/ IRENA) • Europe: approaching targets under WEEE; rest of world lags • Recycled PV supply could meet ~70% of solar silver demand 2040—2050 under NZE pathway (IEA)	• 85—90% of turbine components recyclable via established routes • Blade composite recycling: no solution meeting all three conditions - commercial availability, environmental competitiveness, cost-competitiveness - simultaneously • Repowering rate: growing but permitting timelines remain a constraint

Dimension	**Batteries** Most mature circular ecosystem	**Solar PV** Manufacturing waste overlooked	**Wind** Blade circularity as bottleneck
Defining bottleneck	**Design standardisation + data infrastructure** Heterogeneous battery chemistries and pack designs impede efficient recycling. Without standardised design and digital passports, second-life and end-of-life decisions cannot be made reliably at scale.	**Market viability outside regulatory mandates** Technical feasibility demonstrated. Economics of PV recycling remain fragile without mandates. Recycling rates will not rise without policy forcing functions.	**Material chemistry + market structure** Thermoset blade composites cannot be reprocessed. Recyclate revenues insufficient to cover processing costs. Market structure problem, not just technology gap.
Headline insight	**Recycling is necessary but insufficient.** Design standardisation, digital passports, and logistics infrastructure are the binding agents. Strong policy is what ties them together.	**Manufacturing waste is the overlooked problem.** The end-of-life panel wave is decades away. Kerf loss, silver recovery, and delamination at the factory gate offer more immediate returns.	**Blade recyclability is solvable by design.** Thermoplastic and bio-based resins are ready for policy mandates. Repowering is the rational near-term strategy while long-term infrastructure develops.

Sources: IEA Critical Minerals Data Explorer (2024); IEA Recycling of Critical Minerals (2024); EU Battery Regulation 2023/1542; IRENA End-of-Life Management: Solar PV Panels; NREL thermoplastic blade research; EU WEEE Directive.

4.4 CROSS-SECTOR SYNTHESIS: WHAT THE GLOBAL EVIDENCE TELLS US

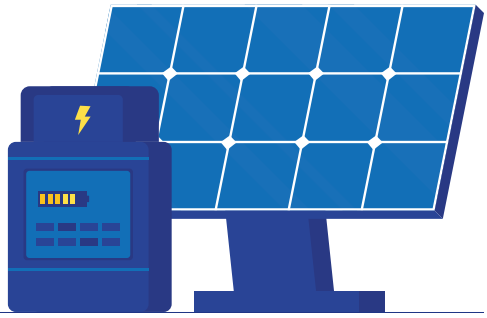
Three convergent findings emerge from the global evidence base across batteries, solar PV, and wind energy, each with direct implications for how governments and industry should prioritise circular economy action.

Design-stage decisions offer the highest policy leverage. The choices made during product design, such as material selection, modularity, fastening methods, and chemical compatibility determine recyclability decades before a product reaches end of life. Yet manufacturers today optimise for performance and cost at point of sale, with no financial exposure to end-of-life consequences. This misalignment between who makes design decisions and who bears disposal costs is a structural market failure. Eco-design requirements, recyclability thresholds as conditions of market access, and extended producer responsibility schemes are more effective than downstream waste management alone. Policy that acts early in the product lifecycle will consistently outperform policy that acts late.

Standardisation is a prerequisite for scale. Circularity at the level of individual products is technically achievable but economically marginal without standardisation. In batteries, heterogeneous pack formats fragment recycling streams and raise processing costs.

In solar PV, the shift to standardised wafer sizes has driven manufacturing learning rates of approximately

24% PER DOUBLING OF CUMULATIVE PRODUCTION



In wind, blade labelling and modular architecture proposals are at an early stage but follow the same logic. Voluntary standardisation rarely moves fast enough; regulatory anchoring or procurement-driven demand signals are typically required.

High-value material recovery is the economic engine. The financial case for circular investment rests on a small number of high-value materials: silver and silicon in PV, cobalt, lithium, and nickel in batteries, and carbon fibre in wind. These represent a fraction of product mass but the overwhelming share of recoverable value. Policy that focuses incentives on bulk materials such as glass or structural steel will not generate revenues sufficient to make circular models self-sustaining. Recycled content mandates, critical mineral strategies, and targeted support for precision recovery technologies should be the priority.

The EU Battery Regulation (2023) is the most advanced example: rather than regulating what happens to a battery after disposal, it regulates the battery as a product, mandating recycled content thresholds, design requirements, carbon footprint declarations, and digital passports as conditions of market entry.

The global policy direction is shifting from waste regulation to product regulation. The EU Battery Regulation (2023) is the most advanced example: rather than regulating what happens to a battery after disposal, it regulates the battery as a product, mandating recycled content thresholds, design requirements, carbon footprint declarations, and digital passports as conditions of market entry. Similar thinking is emerging in solar PV through the EU Ecodesign for Sustainable Products Regulation, and in wind through blade labelling and end-of-life planning requirements. For any jurisdiction seeking to build a competitive cleantech circular economy, this trajectory sets the direction of travel. Aligning domestic standards with emerging international product regulations is not only environmentally rational; it is increasingly a condition of access to major export markets.

4.5 SECTORAL DEEP DIVE: CIRCULAR INTERVENTIONS FOR INDIA

India's cleantech manufacturing has expanded rapidly, but its structural foundations reveal a consistent vulnerability: strong assembly capacity built on imported inputs. The table below applies Porter's value chain framework to India's three core cleantech sectors, namely solar PV, batteries, and wind tracing the full chain from raw material sourcing through manufacturing, distribution, and after-sales service, and mapping India's current position at each stage. The analysis shows that while India has built genuine strength at the assembly and integration stage, it remains heavily dependent on imported critical minerals, processed materials, and advanced components at the upstream end of the chain, where the highest value is created and captured. This structural picture is the essential backdrop for the circular economy interventions discussed in the sections that follow, which target precisely those points in the chain where India's current linear, import-dependent model is most exposed and where circular strategies can most effectively reduce costs, build material security, and strengthen competitive position.

Table: Value Chain of India's Cleantech Manufacturing Industry

Value Generated: The cleantech value chain in India is geared towards a system in which low-carbon technologies are produced domestically at scale, with secure inputs and circular material flows, thereby delivering economic competitiveness, strategic autonomy, and environmental sustainability simultaneously. Thus, the margin in India's cleantech value chain is the transition from dependence to resilience.

Secondary Activities

Policy and Financial Architecture: India's circularity-linked policy architecture has layered fiscal incentives, sectoral missions and regulatory standards.
• PLI schemes:
  · ₹18,100 crore for Advanced Chemistry Cell (ACC) **battery storage** targets 50 GWh of domestic cell manufacturing capacity (Ministry of Heavy Industries, 2021)
  · ₹24,000 crore for high-efficiency **solar PV modules** comprising Tranche I (₹4,500 crore) and Tranche II (₹19,500 crore) support gigawatt-scale module and cell production (MNRE, 2021 and 2022)
• **Battery Waste Management Rules (BWMR) 2022 and E-Waste (Management) Rules 2022** establish regulatory frameworks for end-of-life management across batteries and solar PV
• **Approved List of Models and Manufacturers (ALMM)** for solar modules and cells, and the Revised List of Models and Manufacturers (RLMM) for wind turbines, mandate domestic sourcing for government-backed projects, creating a protected demand base
• **ALMM-II,** mandating domestically manufactured cells in all government-backed solar projects, under implementation from 2026
• **Critical Mineral Mission** launched to secure India's upstream mineral supply chain across exploration, processing, and recovery
Key value-added: Policy-anchored demand certainty, creates a protected domestic market, financial incentives for capacity expansion, and a regulatory framework for environmental and financial compliance.

Secondary Activities

Technology Development: Technology development is mainly driven by adoption, as Indian manufacturers follow global efficiency trends, even as domestic capabilities are developing in certain areas.

Some sectoral Examples:

- **Solar PV:** Manufacturers transitioning from PERC to TOPCon cell architecture; Waaree commissioned a 5.4 GW TOPCon cell plant in Gujarat (2024); India's first ingot-wafer manufacturing facility (2 GW) commissioned in 2025
- **Batteries:** Ola Electric developed the 4680-format Bharat Cell indigenously at its Krishnagiri, Tamil Nadu gigafactory, India's first domestically engineered Li-ion cell receiving ARAI certification under AIS-156 Amendment 4 in 2025
- **Wind:** Adani New Industries advancing blade engineering to 91.2-metre designs at its Mundra, Gujarat facility; serial production underway for next-generation turbine platforms suited to low-wind sites
- **Green energy adjacent:** GAIL exploring green hydrogen blending and carbon capture technologies through JVs with LanzaTech and Accelera

R&D institutions and Innovation: IIT and CSIR laboratories conduct research on recycling technologies, battery chemistries, and material efficiency; MNRE's Renewable Energy Research and Technology Development (RE-RTD) programme funds early-stage innovation in circularity and efficiency. Translation from research to commercial scale remains limited; India has no nationally funded programme equivalent to Europe's DecomBlades or CABRISS composite recycling initiatives.

Key value-added: Incremental efficiency gains through technology adoption, emerging domestic cell design capability, growing blade engineering sophistication, and foundational R&D for next-generation technologies.

Human Resource Management

- **Education:** India's AICTE-approved engineering institutions produce between 1 and 1.5 million engineering graduates annually, providing a substantial pipeline for cleantech manufacturing roles.
- On-the-Job Training:
  - Private companies such as Suzlon, Tata Power Solar, and Amara Raja maintain dedicated on-site training programmes for technicians and engineers at manufacturing facilities
  - The wind sector has developed a mature O&M workforce over three decades of domestic turbine manufacturing and deployment
- Skills gaps
  - In specialised areas such as Hydrometallurgical battery recycling, Composite materials engineering for blade manufacturing, Cell chemistry and electrochemistry, Reverse logistics design and state-of-health battery diagnostics, skill gaps persist
  - No formal qualification framework currently exists for circular economy roles (recycling operations, second-life battery assessment, composite waste management)
- **Job Hazards:** Approximately 500,000 workers are employed in the informal e-waste and battery recycling sector, handling hazardous materials without formal certification or safety infrastructure

Key value-added: Large graduate engineering talent pool, established O&M workforce in wind, growing manufacturing workforce in solar; significant informal recycling employment base requiring formalisation and upskilling.

Secondary Activities

Procurement & Input Sourcing: It operates through two parallel pipelines: primary (virgin) sourcing, which currently dominates, and secondary (circular) sourcing, which remains nascent but strategically critical.

1. Primary Sourcing (Virgin Materials): This stream involves sourcing newly extracted and processed materials and forms the backbone of current manufacturing systems. It is currently Import-dependent, concentrated, and carbon-intensive

- Technology-specific dependencies:
  - Solar PV:
    - Polysilicon: ~100% imported (China-dominant)
    - Silver: >70% imported
    - Solar cells: ~64% of demand met through imports
  - Batteries:
    - Lithium, cobalt, nickel: near-total import dependence
    - ~80% of Li-ion cells are sourced from China, Japan, and South Korea
    - Annual critical mineral import bill: ~$2.5 billion
  - Wind:
    - Steel and copper: largely domestic
    - Rare earths (magnets): almost entirely imported
    - Gearbox castings (~90%) and specialised components: import-dependent
- Structural characteristics
  - High import dependence for critical and high-purity inputs
  - Geographically concentrated supply chains, exposing India to geopolitical risks and price volatility
  - Limited domestic midstream capabilities (refining, chemical processing)
  - High energy and carbon intensity embedded in upstream production

2. Secondary Sourcing (Circular Materials): This stream involves sourcing from recovered, reused, and recycled materials, offering a pathway to reduce import dependence and supply risk. Emerging, domestic, and resource-efficient

- Key sources: End-of-life solar panels (glass, aluminium, silicon recovery), Used EV and stationary batteries (lithium, cobalt, nickel recovery; second-life use), Industrial scrap and production waste
- Structural characteristics:
  - Nascent but growing ecosystem, constrained by limited end-of-life volumes
  - Reduces import dependence and embedded emissions
  - Mix of informal recovery systems and emerging formal recycling industry
  - Technological and economic constraints in high-purity material recovery
  - Weak market signals and policy enforcement for recycled content

Key value-added: Diversification of upstream mineral sourcing, expansion of domestic component ecosystems, and cost rationalisation through targeted duty exemptions collectively enhance competitiveness, supply security, and sustainability.

Primary Activities

Resource Origination & Strategic Inputs

This stage captures the material and energy inputs required for cleantech manufacturing. High import dependence and geographic concentration of supply chains cause exposure to price volatility and geopolitical risks. Limited domestic refining and midstream capabilities, with high energy-carbon intensity of inputs. Policy responses include the National Critical Mineral Mission (2025) and recycling incentives.

1. **Solar PV:** Strong assembly base, but high upstream import dependence

- Polysilicon: ~100% imported
- Silver: >70% imported
- Solar cells: 68% by value from China in FY26; total cell import bill ₹22,021 crore, with volume growing 5.6× since FY23 as prices collapsed
- Domestic inputs: glass and aluminium frames

2. **Batteries:** Deep import dependence across the value chain

- Lithium, cobalt, nickel: ~100% imported (~$2.5 billion annually)
- Li-ion cells: ~80% imported (China, Japan, South Korea)
- Domestic manufacturing constrained (PLI-ACC delays due to import dependence on equipment/technology)
- Strategic shift: overseas sourcing (e.g., lithium assets in Argentina)

3. **Wind:** Partial localisation with reliance on high-value imports

- Domestic: steel and copper (towers, nacelles)
- Imported: rare earths (near 100%), gearbox castings (~90% from China), specialised components,blade inputs

Processing, Intermediate Manufacturing & Assembly

India's cleantech sector has a strong downstream presence in final assembly, but upstream material processing remains the main bottleneck. Strategic government interventions like PLI schemes, ALMM, and ACC policies have quickly scaled up and increased standardisation and formalisation board.

1. **Sector-Specific Maturity**

- Solar PV: This is India's strongest suit, with 74 GW of module assembly capacity as of March 2025. The industry is currently undergoing a technological pivot toward high-efficiency TOPCon cell technology, projected to dominate the domestic market by 2027.
- Wind Energy: Over three decades, India has become the world's third-largest wind manufacturing base. Annual turbine capacity is at 20 GW, and blade capacity exceeds 15 GW, with 70—80% of turbine components now manufactured domestically.

Batteries & Storage: While battery pack assembly is well established (led by players such as Tata, Amara Raja, and Exide), indigenous cell production is the new frontier. Ola Electric is leading this shift with its 4680 Bharat Cell, produced at its Tamil Nadu gigafactory.

The manufacturing stage can be divided into two distinct layers of activity:

1. **Material Processing & Intermediate Manufacturing:** Converting raw inputs into industrial sub-components (e.g., Polysilicon to wafers; Cathode/Anode synthesis; Electrolyte & membrane production). Currently characterised by high dependence on China and East Asia, domestic capacity is still catching up.
2. **Core Manufacturing & Assembly:** The visible layer where final products are built (e.g., Cell fabrication, module assembly, battery pack formation, QA, and certification).Significant momentum in solar and wind, with emerging capabilities in battery cells and green hydrogen.

Primary Activities

Distribution & Project Deployment

India's clean energy sector has evolved into a sophisticated, dual-track ecosystem where robust domestic manufacturing increasingly feeds both national welfare schemes and high-value global export markets.

1. **Solar**: India's solar sector has around 40 GW capacity linked to decentralized initiatives like PM Surya Ghar and PM-KUSUM. Strict rules under ALMM List-II will protect domestic cells from June 2026. India also became a key non-China supplier, exporting 4.5 GW of modules in 2024, mainly to the US and EU.
2. **Wind**: The wind sector, a mature industry, hit a record 6.3 GW of new installations in 2025, nearly doubling previous figures. With 20 GW of domestic turbine capacity exceeding demand, 17 Indian manufacturers are expanding globally, supplying turbines and blades to Australia, Brazil, and Europe.
3. **Battery**: This export-driven growth is reflected in the battery sector, dominated by electric two- and three-wheelers, which hold over 95% of the EV market, while grid-scale storage expands with government support. Though formal recycling is a gap, emerging battery swap networks like Sun Mobility are showing the standardised collection systems needed to support India's growing cleantech goals.

Market Access & Demand Formation

Cleantech markets in India are policy-mediated, with market access, pricing, and scale shaped by regulatory frameworks rather than purely by competitive forces. Domestic manufacturing is often tied to eligibility criteria and compliance requirements, while export competitiveness is emerging but uneven.

Market architecture:

1. Government-led demand creation: tenders, auctions, and viability gap funding
2. Domestic content frameworks: ALMM/RLMM compliance linking market access to local manufacturing
3. Long-term offtake mechanisms: power purchase agreements, hydrogen supply contracts
4. Price discovery: regulated and semi-regulated mechanisms
5. Export development: gradual integration into global markets

Technology-specific pathways:

1. Solar PV: Central and state-led tenders (MNRE, state agencies) drive deployment
2. Batteries: Demand anchored by subsidies (FAME, PM E-DRIVE) for EV adoption
3. Wind: RLMM approval required for participation in public projects, ensuring quality and domestic sourcing

Primary Activities

Circular Recovery & Reverse Logistics

This stage distinguishes cleantech from traditional manufacturing by enabling the return of materials into the production cycle through collection, recovery, and reuse. The ultimate objective is reintegration into upstream supply chains or extended product use.

1. Core activities:

- Collection of end-of-life panels, batteries, and components
- Sorting, testing, and grading
- Repair and refurbishment (e.g., second-life batteries)
- Dismantling, material recovery, and recycling of critical materials

2. System characteristics:

- Policy recognition exists, but systems remain nascent
- Significant future opportunity as waste volumes increase
- Strong role of the informal sector, highlighting the need for formalisation

Technology-specific status:

3. Solar PV:

- End-of-life systems at an early stage
- Producers required to store waste panels until ~2034—35
- 550 producers registered under EPR, but no mandatory recycling targets yet

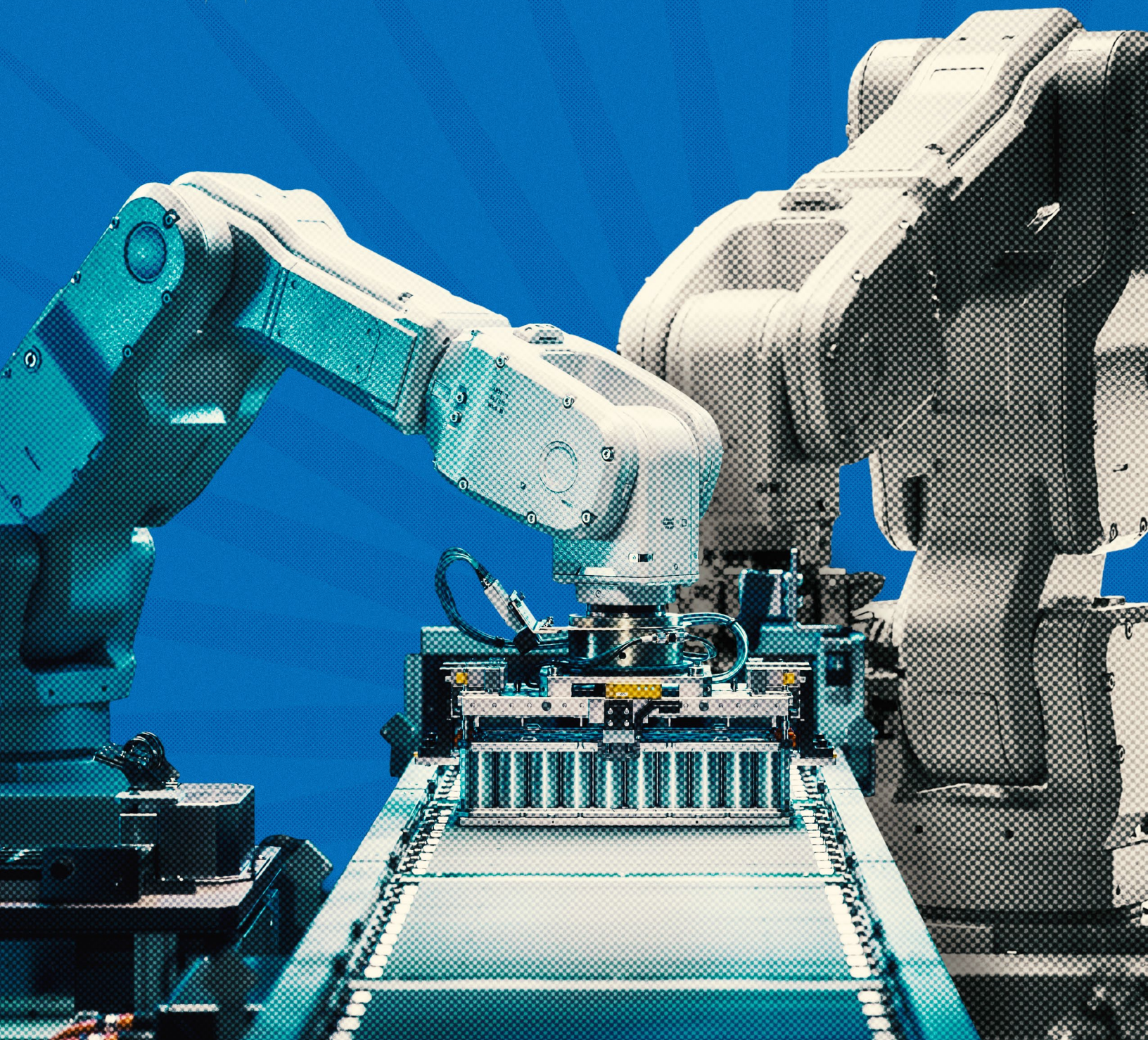
4. Batteries:

- Battery Waste Management Rules mandate 70% collection of batteries placed in the market in a lagged reference year, and 90% material recovery for EV batteries from FY2026-27
- Digital credit system in place
- 18% tax on retired batteries disincentivises formal recycling, favouring informal channels

5. Wind:

- Repowering policy (2023) enables turbine upgrades
- No clear pathway for blade/component recycling
- Absence of EPR or end-of-life regulation

05



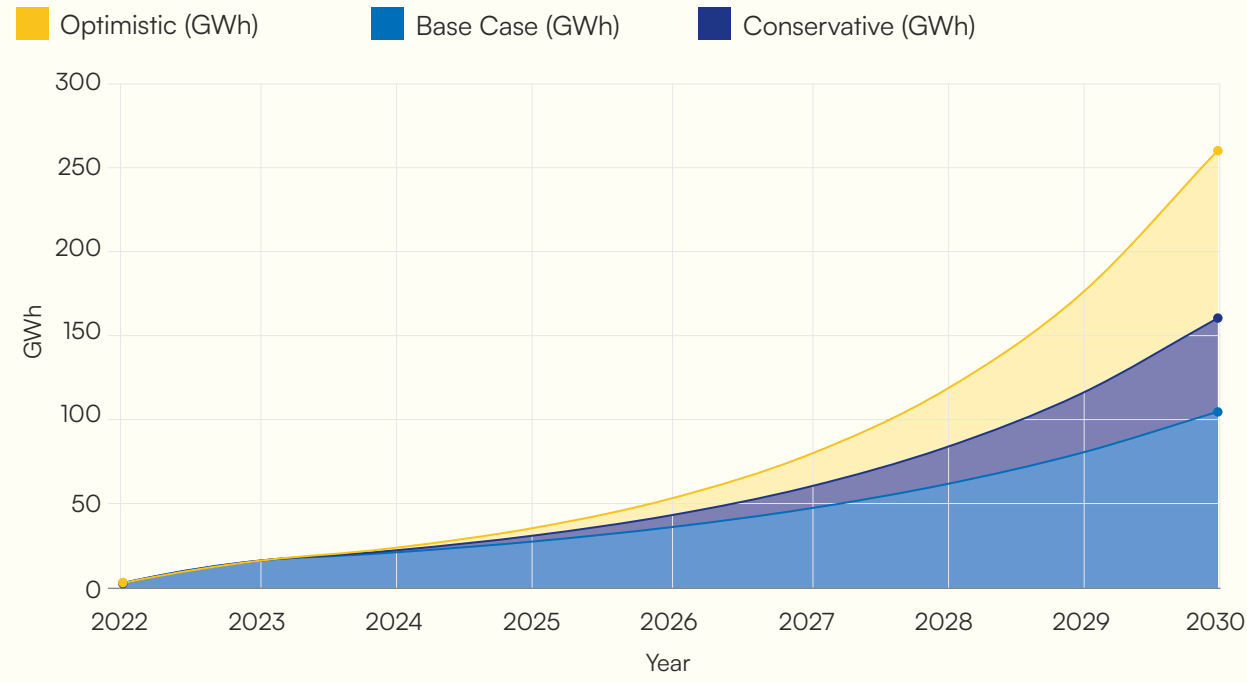
BATTERIES – CIRCULAR MANUFACTURING PATHWAYS FOR INDIA

Snapshot of current state

India's battery sector sits at a pivotal juncture: rapid demand growth, relatively nascent domestic manufacturing, a strong but unevenly implemented policy framework, and a recycling ecosystem that is only emerging to absorb the waste wave that is approaching. India's demand for lithium-ion batteries is expected to rise at a pace of 26% annually, growing from 16 GWh in 2023 to 248 GWh in annual demand by 2035[38]. This growth is driven by electric mobility, grid storage, and consumer electronics. India's annual LIB demand is projected to reach 127 GWh by 2030, with the government targeting self-reliance as approximately 75% of current imports come from China[39]. Cumulative lithium-ion battery demand across all segments is expected to reach an estimated 600 GWh over 2022—2030, as the government plans to have 80 million EVs on Indian roads by 2030[40].

The chart below traces India's projected annual LIB demand from 2022 to 2030 across three demand scenarios conservative, base case, and optimistic modelled by NITI Aayog. Even under the most conservative trajectory, annual demand rises over ten-fold over the decade. The base case, which underpins most policy planning, points to around 160 GWh of annual demand by 2030 and a cumulative market of 600 GWh.

Figure 6.1: India's lithium-ion battery demand trajectory, 2022—2030



Source: NITI Aayog report

Therefore, the structural vulnerability of India's battery economy is stark. India remains largely dependent on imports for critical battery minerals, with nearly 100% import dependency for lithium, cobalt, and nickel[41]. India lacks major operational lithium and cobalt mines, relying almost entirely on imports, which cost approximately $2.5 billion annually[42]. This dependence is geographically concentrated: minerals at high risk with heavy import dependency and reliance on very few source countries include synthetic and natural graphite, lithium oxide, nickel oxide, nickel sulphate, and copper cathodes[43]. India's import dependency will likely continue, as demand for critical minerals is expected to more than double by 2030, while domestic mines will take more than a decade to start producing[44].

The Government of India launched the Production Linked Incentive (PLI) Scheme for Advanced Chemistry Cell (ACC) Battery with a significant financial outlay of ₹18,100 crore to establish 50 GWh of domestic manufacturing. However, progress has been uneven. As of early 2025, none of the beneficiaries had met the December 2024 milestones, resulting in no disbursement. Delays were attributed to continued reliance on China for key components and technology, with supply chain disruptions significantly impeding progress[45]. India's announced manufacturing capacity would cover only a quarter of its projected demand in the IEA's Announced Pledges Scenario, underscoring significant gaps that could increase the risk of failing to meet long-term decarbonisation targets without heavily relying on imports[46].

Currently, India's recycling capacity stands at only about 0.3% of battery waste produced, though it is expected to grow beyond 50% by 2030 due to increased demand for lithium-ion battery applications[47]. End-of-life lithium-ion battery availability is expected to increase from 19 kilo tonnes in 2023 to 233 kT by 2035, growing at 26% annually[48].This twelvefold rise within a decade is the volume against which India's collection and processing infrastructure must now be built[49].

The informal sector dominates current collection and processing, and it handles nearly 62% of India's electronic waste and employs half a million people who often use unsafe and unscientific methods to extract materials. In contrast, the formal system remains thinly spread, with just 2,808 authorised collection centres serving a population of over 1.4 billion. An 18% GST levied on retired batteries in the formal sector incentivizes the informal sector to play a significant role in the recycling industry, compromising worker safety and environmental standards[50]. The Battery Waste Management Rules (BWMR) 2022 and the Extended Producer Responsibility (EPR) framework ensure that manufacturers actively participate in battery collection and recycling, minimising environmental hazards and promoting a circular economy. The policy timeline has been actively updated: after the Draft Battery Waste Management Rule in 2020, the BWMR was enacted in August 2022, followed by amendments in 2023 and 2024, each strengthening EPR provisions and sustainable manufacturing requirements. The Critical Mineral Mission was also launched, aimed at reinforcing India's critical mineral value chain across all stages from exploration and mining to beneficiation, processing, and recovery. The Government of India has eliminated customs duties on 25 minerals and, in the Union Budget 2025—26, proposed to fully exempt cobalt powder and waste, scrap of lithium-ion batteries, lead, zinc, and 12 more critical minerals to secure their availability for manufacturing[51].

India's battery policy evolution: key milestones 2020—2025

2020

Type
REGULATION

Milestone

BWMR Draft circulated

Key provision

Ministry of Environment circulates draft Battery Waste Management Rules; introduces EPR framework concept for battery producers and importers.

2021–22

Type
PROGRAM/POLICY

Milestone

ACC PLI Scheme & Mission LiFE

Key provision

₹18,100 crore PLI scheme for Advanced Chemistry Cell manufacturing with 50 GWh domestic capacity target. Mission LiFE frames circular resource use as a national behavioural priority.

AUG 2022

Type
REGULATION

Milestone

Battery Waste Management Rules 2022 (BWMR)

Key provision

EPR mandatory for all battery producers. Collection targets set at 770% of the quantity placed in the market in a lagged reference year; material recovery targets rise from 70% in FY2024-25 to 80% in FY2025-26 and 90% from FY2026-27. Centralised EPR portal under CPCB. Covers EV, industrial, portable, and automotive batteries.

2023

Type
REGULATION

Milestone

BWMR Amendment 2023

Key provision

Recycled content targets introduced: 5% from FY2027-28 rising to 20% from FY2030-31 for EV and industrial batteries. Strengthened recycler registration requirements under CPCB.

2023

Type
MISSION

Milestone

National Critical Mineral Mission

Key provision

Lithium, cobalt, nickel, and graphite designated strategic minerals. Domestic recycling mandated as a supply-chain security lever alongside mining and international sourcing.

2024

Type
REGULATION

Milestone

BWMR Amendment 2024

Key provision

Expanded EPR obligations for importers and e-commerce platforms. Steeper penalties for non-compliance. Aligns recycled content targets with ACC PLI scheme milestones.

FEB 2025

Type
FISCAL

Milestone

Union Budget 2025—26: duty exemptions

Key provision

Full BCD exemption on 35 capital goods for EV battery manufacturing. Customs duty removed on cobalt powder, lithium-ion battery waste/scrap, and 12 other critical minerals directly lowering cost of recycled material inputs.

Sources: MoEFCC — BWMR 2022 & amendments; Ministry of Mines, National Critical Mineral Mission 2023; Union Budget 2025—26 memorandum; PIB press releases.

5.1 KEY CIRCULAR INTERVENTION AREAS

Batteries: Snapshot table

Intervention area	Sub-interventions	Current state in India	Key mechanism / action
A Design & Manufacturing	• Standardised battery formats • Design for disassembly (DfD) • Low-energy / dry electrode manufacturing	Market fragmented across formats (cylindrical, prismatic, pouch), chemistries (NMC, LFP, NCA), and pack architectures[52]. Adhesive bonding makes disassembly destructive; second-life assessment nearly impossible. Conventional wet electrode process uses toxic NMP solvent; energy-intensive recovery required.	• Mandate format harmonisation within E2W and E3W categories (95% of 2024 EV sales) via BWMR / EPR targets • Embed explicit DfD mandates mechanical fastening, modular units as PLI scheme conditions • Adopt dry electrode technology in new gigafactories from outset (~50% lower capex, ~60% smaller facility)

Intervention area	Sub-interventions	Current state in India	Key mechanism / action
B **Manufacturing Process**	• Cathode scrap recovery loops • Water and solvent recycling • Renewable-powered gigafactories	In-process CAM scrap, trimming waste, and formation rejects generate thousands of tonnes per year of high-value material (Co, Ni, Li). Electrolyte and electrode washing create hazardous solvent streams; India's gigafactory sites include water-stressed regions. Battery manufacturing carbon intensity is electricity-driven; India's solar tariffs now below ₹2/ kWh	• Mandate co-location of scrap recovery or formal offtake with licensed recyclers as PLI condition; 85—95% CAM recovery achievable • Deploy closed-loop membrane filtration and reverse osmosis systems; 60—80% freshwater intensity reduction possible • Require captive or contracted renewable power for PLI-supported gigafactories
C **Value Chain & Second Life**	• Second-life battery integration • Reverse logistics systems • Battery passport / SOH protocols	EV batteries retired at 70—80% capacity retain significant storage potential. Grid-scale storage demand projected at 27 GW / 108 GWh by 2030 (CEA, 2023). Collection infrastructure fragmented; formal reverse logistics absent in tier-2 and tier-3 cities. BWMR EPR credit system in place but enforcement uneven. No national battery passport or standardised SOH assessment protocol yet exists.	• Deploy standardised SOH assessment protocols as precondition for second-life markets • Use BWMR EPR credit system to catalyse formal collection; scale battery exchange models (Bounce Infinity, Sun Mobility) to tier-2/3 cities • Introduce national digital battery passport recording chemistry, cycle count, and health data
D **Recycling Technology**	• Mechanical / black mass processing • Hydrometallurgical refining • Direct recycling (frontier) • LFP chemistry challenge	Dominant method today: low-cost shredding to black mass. Output cannot re-enter cell manufacturing; sold to downstream smelters, often abroad. Lohum (USD 54M Series B, 2024) and Attero (INR 8,300 crore investment, 2024) leading hydromet transition. No commercial-scale direct recycling. LFP chemistry favoured by India's gigafactories has lower residual value; recycling uneconomical without regulatory mandate.	• Transition to hydromet: up to 95% high-value metal recovery; battery-grade output re-enters cathode precursor production • Support direct recycling R&D through Critical Mineral Mission partnerships with IITs and national labs • Embed mandatory LFP recycling requirements into BWMR cannot rely on market incentives alone • Scale cluster-based Common Facility Centres (NITI Aayog recommendation) to formalise informal sector

A Design and Manufacturing: Building Circularity from the Cell Up

Circular economy logic demands that end-of-life management is designed in, not retrofitted. For batteries, this means decisions made at the cell design stage ranging from chemistry selection, format standardisation, binder choice, and modular architecture that determine the viability and economics of recycling decades later.

Standardised battery formats: India's EV market is currently fragmented across formats (cylindrical, prismatic, pouch), chemistries (NMC, LFP, NCA), and pack architectures[52]. This heterogeneity imposes enormous costs on downstream recyclers who must manage multiple disassembly pathways. Drawing on the European Union's Battery Regulation (EU) 2023/1542 as a reference, which mandates recycled content thresholds and traceability requirements, **India's BWMR and forthcoming EPR targets should establish format harmonisation, at least within EV two-wheeler and three-wheeler categories which together constituted nearly 95% of all Indian EV sales in 2024[53].**

Design for disassembly (DfD): Cell-to-pack and module-level designs that allow non-destructive disassembly are critical. Current architectures using adhesive bonding between cells and structural integration of battery packs improve performance but make recycling more difficult and second-life assessment nearly impossible. DfD principles require mechanical rather than adhesive fastening, colour-coded and standardised wiring, and modular replacement units. The BWMR 2022 encourages refurbishment and reuse, but explicit Design for Disassembly requirements for manufacturers including those supported under India's PLI scheme remain absent from the regulatory framework[54].

Low-energy manufacturing: The conventional wet electrode manufacturing process for lithium-ion batteries relies on N-methyl-2-pyrrolidone (NMP) as a solvent, which is a toxic substance requiring energy-intensive recovery systems. Dry electrode manufacturing bypasses the need for solvent blending and solvent evaporation processes, resulting in shorter production time, reduced energy consumption, and lower equipment investment. Capital investment for dry electrode processes can be approximately 50% that of wet processes, with facility sizes shrinking by around 60%[55]. **As India constructs its first gigafactories, embedding dry electrode technology from the outset rather than retrofitting it later would lock in circular manufacturing advantages.**

B Manufacturing Process: Closing Loops Within the Factory Gate

Circular manufacturing interventions within the production process itself are often the fastest and most economically viable pathways, because they operate within existing factory systems and reduce input costs directly.

Cathode scrap recovery loops: In a battery gigafactory, electrode production generates significant quantities of "in-process scrap" cathode active material (CAM) that does not meet quality specifications, trimming waste from electrode rolls, and formation cycle rejects. At scale, this scrap constitutes thousands of tonnes per year of high-value material (cobalt, nickel, lithium). Closed-loop scrap reprocessing either on-site or through proximate third-party processors can recover 85—95% of this material and reintegrate it into cathode precursor production[56]. By 2030, battery production scrap is expected to account for half of the supply for battery recycling plants globally and scrap materials remain in an almost pristine state, making them much easier and cheaper to recycle and feed back into the manufacturing plant[57]. **India's**

nascent gigafactories should mandate co-location of scrap recovery facilities or formal offtake agreements with licensed recyclers as a PLI condition.

Water and solvent recycling: Electrolyte production, electrode washing, and cell formation involve significant water consumption and hazardous solvent streams. Closed-loop water treatment systems including membrane filtration, reverse osmosis, and electrolyte recovery can substantially reduce freshwater intensity in battery manufacturing facilities, with engineered water reuse strategies shown to offset a meaningful share of total facility water demand[58]. This is particularly relevant for India, where gigafactories in water-stressed regions such as Rajasthan and parts of Gujarat face supply risks.

Renewable-powered gigafactories: The carbon intensity of battery manufacturing is significantly determined by the electricity used in the process. The IEA's Net Zero Emissions Scenario estimates that recycling, combined with alternative chemistries and behavioural changes, could reduce lithium demand by 25% by 2030[59]. Pairing this with low-carbon manufacturing is essential for India to position its batteries as credibly green for export markets. India's solar tariffs, which reached a record low of ₹2/kWh in 2020 and have remained in the ₹2.15—2.6/kWh range in recent auctions, make on-site or captive renewable power for gigafactories increasingly viable[60].

C Value Chain: Second Life and Reverse Logistics

Second-life battery integration: EV batteries are typically retired when their capacity falls to 70—80% of original rated capacity and they can no longer meet the range and performance requirements of mobility, but they retain substantial energy storage potential. At this stage, batteries can still serve as stationary storage for renewable energy farms, backup power for commercial buildings or telecom towers, and grid balancing applications. This second-life stage can extend a battery's utility for another 5—10 years[61]. For India, where grid-scale battery storage requirements are projected by the Central Electricity Authority to reach 41.65 GW/236 GWh by 2030—32, second-life batteries offer a significant cost advantage over new systems[62].

Realising the potential of second-life batteries in India requires two foundational conditions that do not yet exist at scale. First, standardised protocols for assessing battery state-of-health (SOH) are needed so that retired packs can be reliably evaluated for reuse rather than defaulted to recycling. Second, a formal collection and reverse logistics infrastructure must be developed[63]. Hence there is a need for a national battery passport system or a digital record of each battery's chemistry, cycles, and health as a precondition for viable second-life markets.

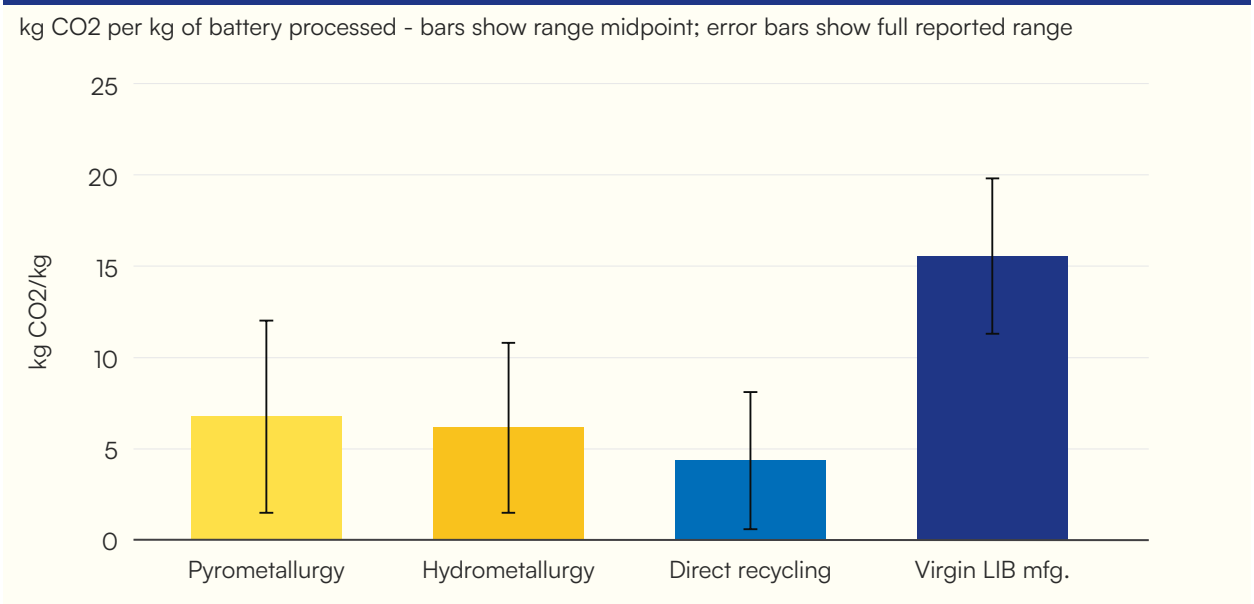
Reverse logistics systems: India's collection infrastructure for end-of-life batteries is fragmented. The BWMR 2022 mandates a phased EPR collection target of 70% of batteries sold in an earlier year but formal reverse logistics networks capable of reaching tier-2 and tier-3 cities remain underdeveloped. After collection, they must get them recycled by an authorised recycler, who then shares recycling credits with the producer on a digital portal. This EPR credit system, if rigorously enforced, can catalyse investment in formal collection infrastructure. Industry models such as battery exchange networks, already deployed by Bounce Infinity and Sun Mobility in India's two-wheeler segment provide proof-of-concept for nationwide reverse logistics at scale.

D Recycling: Technology Transition for High-Value Recovery

India's dominant recycling method today is mechanical/physical processing or shredding battery modules to produce "black mass"; a mixture of cathode active materials, graphite, and metals. While low-cost and technically straightforward, physical/mechanical recycling is the largest process category in India because it is far simpler, cheaper, and quicker to deploy than chemical-refining methods, requiring lower capital investment and widely available equipment. However, this process does not recover materials to battery-grade purity, meaning the output cannot be directly re-entered into cell manufacturing and must instead be sold to downstream smelters often abroad.

Hydrometallurgical processing using aqueous chemical leaching to extract and separate individual metals produces high-purity battery-grade materials that can be directly reintegrated into cathode precursor production. Hydrometallurgy-based solutions can recover up to 95% of high-value metals while reducing carbon emissions, creating a closed-loop supply chain[64]. The emissions advantage of moving up the recycling technology ladder is measurable. As shown in the Figure below , direct recycling produces the lowest greenhouse gas emissions across its reported range (0.6—8.1 kg CO_2/kg), while pyrometallurgy - the most energy-intensive process shows the widest variance (1.5—12 kg CO_2/kg), reflecting its dependence on high-temperature smelting and feedstock composition. Hydrometallurgy occupies a middle position, with a comparable lower bound but a narrower overall range, making it a more predictable emissions pathway at scale.

Figure 6.2: **Greenhouse gas emissions by lithium-ion battery recycling pathway**



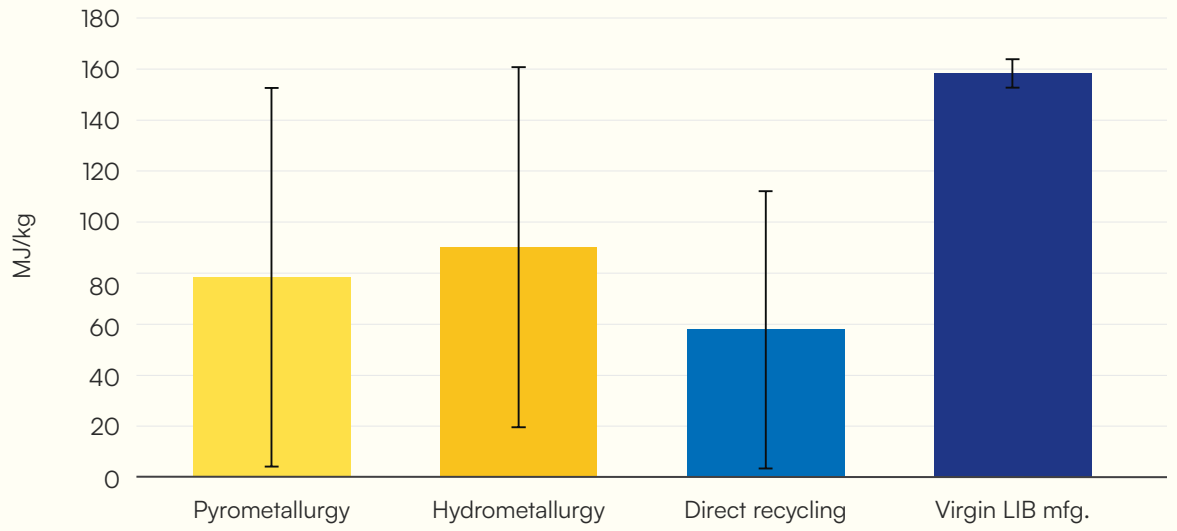
Reported ranges (kg CO2/kg)-Pyrometallurgy: 1.5-12 | Hydrometallurgy: 1.5-10.8 | Direct recycling: 0.6-8.1 | Virgin LIB manufacturing: 11.3-19.8

Source: Das et al., Table 10-Separation and Purification Technology 382 (2026) 135847

The energy intensity story reinforces the case for technology transition. Direct recycling has the lowest energy floor at 3.5 MJ/kg, while virgin LIB manufacturing remains consistently the most energy-demanding process at 152.9—163.8 MJ/kg underlining the systemic energy savings a mature domestic recycling industry would deliver[65].

Figure 6.3: **Total energy consumption by lithium-ion battery recycling pathway**

MJ per kg of battery processed -bars show range midpoint; error bars show full reported range



Reported ranges (MJ/kg) - Pyrometallurgy: 4.2-152.5 | Hydrometallurgy: 19.6-160.7 | Direct recycling: 3.5-112.1 | Virgin LIB manufacturing: 152.9-163.8

Source: Das et al., Table 10-Separation and Purification Technology 382 (2026) 135847

Globally, significant efforts are being made to transition from pyrometallurgical to hydrometallurgical approaches, which are less energy-intensive and more environmentally sound; sulfate-based leaching is currently the only large-scale hydrometallurgical method used commercially for lithium-ion battery recycling[66].

Direct recycling: the frontier. Direct recycling which recovers cathode active material in its original crystalline form without chemical breakdown is the most energy- and material-efficient pathway. It is the most effective in reducing lifecycle environmental impacts, while hydrometallurgical recycling provides more limited sustainability benefits for high-performance batteries[67]. While direct physical and biometallurgical recycling are more environmentally and economically favourable, pyrometallurgy and hydrometallurgy are currently preferred owing to their greater technological preparedness. **India currently has no commercial-scale direct recycling operations. This represents both a technology gap and a first-mover opportunity, particularly for Indian R&D institutions and start-ups in partnership with government labs under the Critical Mineral Mission[68].**

06



SOLAR PV – CIRCULAR MANUFACTURING PATHWAYS FOR INDIA

Current State

India's solar PV sector is undergoing one of the most rapid manufacturing expansions in the world , but this extraordinary growth carries within it the seeds of a future waste and resource crisis that policy and industry are only beginning to acknowledge. **Understanding the current state requires examining three distinct but interconnected dimensions: manufacturing capacity, waste accumulation, and the policy framework meant to manage it.**

Manufacturing expansion: India's solar manufacturing scale-up over the past three years has been remarkable. In just one-year, solar module manufacturing capacity nearly doubled from 38 GW in March 2024 to 74 GW in March 2025. Solar PV cell manufacturing similarly rose from 9 GW to 25 GW over the same period, alongside the commissioning of India's first ingot-wafer manufacturing facility at 2 GW[69]. Looking further ahead, India's solar module manufacturing capacity is expected to reach 215—220 GWp by FY2028, supported by cumulative capital expenditure exceeding INR 55,000 crore. With domestic module and cell output expected to exceed domestic requirements, exports are expected to be the key growth driver for the sector going forward. This expansion is geographically concentrated. Gujarat hosts approximately 45% of India's national module production capacity and 52% of cell manufacturing facilities, followed by Tamil Nadu (10%) and Rajasthan (8%) for modules, while Karnataka (18%) and Telangana account for significant cell production capacity[70]. Despite this growth, dependency on imported cells remains significant and is accelerating faster than the headline rupee figures suggest. Customs data shows India imported 6.89 billion cells in FY26 which is 5.6 times the FY23 volume while the import bill grew only 107%, from ₹10,648 crore to ₹22,021 crore, because Chinese oversupply-driven price collapse compressed unit costs by 63% over the same period. At pre-oversupply prices, the FY26 cell import bill would have been approximately ₹59,445 crore. The sector occupies a paradoxical position: rapidly becoming a global manufacturing hub while still deeply dependent on upstream imports at a volumetric scale the value figures alone do not reveal.

6.1 THE POLICY FRAMEWORK

Solar PV modules and cells were formally brought under India's E-Waste (Management) Rules, 2022, effective from April 1, 2023, making India perhaps the second country after the European Union to bring solar PV waste under a national policy framework[71]. Under these rules, solar PV module and cell producers are mandated to store the waste generated from solar PV modules and cells up to 2034—2035 as per the guidelines laid down by the Central Pollution Control Board (CPCB), and file annual returns on the e-waste management portal[72]. The rules also mandate registered recyclers to recover materials as specified by the CPCB.

Around 67% of this waste is expected to be generated in five states: Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Andhra Pradesh. India's cumulative waste from existing and projected solar capacity installations could reach approximately 600 kt by 2030 according to estimates by CEEW, supported by the Ministry of New and Renewable Energy.

However, implementation gaps are substantial. Since guidelines are still being developed, there are limited details on collection mechanisms and technical procedures for processing or recycling the waste. Recycling or recovering most materials is not yet considered profitable due to lack of awareness, high upfront costs, investment risks, and underdeveloped infrastructure and technology[73]. As of late 2024, 552 solar panel and cell producers were registered on the E-Waste EPR Portal, though EPR targets do not yet apply to solar PV waste, meaning manufacturers currently have no mandatory EPR recycling obligations. Furthermore, the Department of Science and Technology has issued a call for proposals on the recovery and recycling of end-of-life solar PV panels, and the Ministry of Mines has launched a recycling incentive scheme with an outlay of INR 1,500 crore under the National Critical Mineral Mission to build domestic capabilities for recovering critical minerals from e-waste and end-of-life components.

India currently sits in what might be called the "installation phase" and the waste wave from the first generation of mass-deployed modules has not yet arrived, but projections make clear it is coming at scale. India's installed 66.7 GW of solar capacity as of FY2023 had already generated about 100 kilotonnes of cumulative waste; this will increase to 340 kt by 2030. Around 67% of this waste is expected to be generated in five states: Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Andhra Pradesh. India's cumulative waste from existing and projected solar capacity installations could reach approximately 600 kt by 2030 according to estimates by CEEW, supported by the Ministry of New and Renewable Energy. Taking the longest view, India's cumulative solar PV waste will reach approximately 19,000 kt by 2050 as all capacity deployed until 2030 reaches end-of-life[74].

The recycling ecosystem is structurally underdeveloped. Commercial recycling of solar PV modules is still at an early stage worldwide, with only a few recyclers operating in countries such as Germany, Italy, France, Japan, South Korea, Australia, and the United States. The main challenges include the lack of local markets for secondary materials, reverse logistics difficulties, and limited recycling technology, leading to high costs and low revenues[75]. India's solar PV recycling industry remains nascent, with only a handful of small-scale operators and no dedicated large-scale commercial recycling infrastructure.

6.2 THE IMPORT DEPENDENCY IMPERATIVE: WHAT THE TRADE DATA REVEALS

India's solar import dependency is not a new concern. It has been flagged in policy documents, industry assessments, and energy transition reports for several years. In this analysis, below we are adding the numbers to capture the actual transaction record that shows, year by year and component by component,

what India is buying, from whom, and in what physical quantities. This analysis fills that gap directly, drawing on trade data that is rarely examined at this level of granularity. The finding that emerges is that India's solar import bill looks broadly stable in rupee terms, which is the lens through which trade dependency is almost always discussed, while the physical volumes flowing in have grown at a pace that would be alarming if the price collapse masking them were to reverse. That gap between what the money shows and what the tonnage shows is the analytical contribution. It means that every policy conversation about solar self-reliance that has relied on value-based trade figures has been overlooking the alarming rise in volume of imports. The second contribution is in the sequencing: this analysis traces how each policy intervention to reduce dependency such as the duty on modules, the ALMM mandate has not reduced the underlying exposure but relocated it one step upstream, from modules to cells, and now toward wafers. That is not a critique of the policy; it is a structural finding about how supply chain dependency behaves when you compress it from one end. It is precisely this finding that the dependency retreats rather than resolves which makes the circular economy argument not aspirational but urgent. The materials flowing into India through these import channels are not just production inputs; they are, in time, a recoverable domestic resource. The question is whether India has built the infrastructure to treat them that way.

India's solar manufacturing expansion is real and remarkable, but the upstream foundation on which it rests is exposed in ways that standard narratives about import dependence do not fully capture. Trade data from DGFT across tells a more urgent story than percentage-share figures alone suggest. It starkly reveals India's volume dependency that is growing far faster than value dependency, geographic concentration that approaches total reliance in the most upstream segments, and a structural condition that will not be resolved by manufacturing scale-up alone. It is also, when read in the right direction, the strongest possible argument for why circularity is not an environmental add-on to India's solar ambition but is an industrial necessity.

The Bill: What India Actually Spent

The most direct measure of India's upstream solar dependency is its direct import bill and the foreign exchange spent on the three components that sit at the heart of solar manufacturing: undiffused silicon wafers (the upstream raw material that feeds cell production), unassembled photovoltaic cells (the core active component assembled into modules), and assembled modules and panels.

India's Direct Solar Import Bill - Layer 1 (₹ Crore)

Component	HS Code	FY23	FY24	FY25	FY26
Silicon Wafers	38180010	1576	2739	1324	2877
Solar Cells (unassembled)	85414200	10648	15335	13905	22021
Solar Modules/Panels	85414300	7445	36134	18263	6675
Total Direct Solar Import Bill		₹19,669 cr	₹54,208 cr	₹33,493 cr	₹31,572 cr

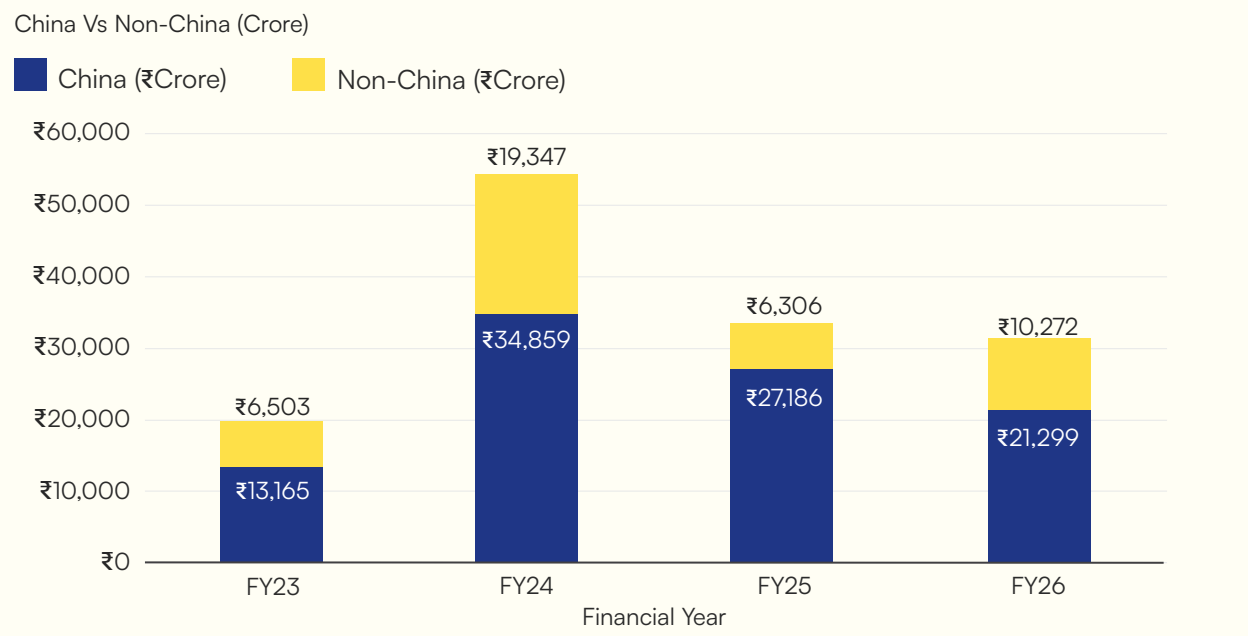
Source: DGFT Trade data

At ₹31,572 crore in FY26 which is yet to be over, India's direct solar import bill is already substantial. However, the aggregate figure, and the apparent stability between FY25 and FY26, Conceal certain important aspects regarding the shift in the composition of solar import. **India has successfully beaten back module imports through policy, only to find cell imports surging to fill the gap. This is not a reduction in dependency, but it is a migration of dependency upstream.**

The aggregate figures also reveal a value-volume divergence that is even more striking than the component-level data alone suggests. Across all three HS codes combined, India's total direct solar import bill grew by 61% in rupee terms between FY23 and FY26. The physical volume of components flowing in over the same period grew by 458% which is 7.6 times faster than the value. The total bill nearly tripled in a single year between FY23 and FY24, reaching a peak of ₹54,208 crore, before policy compressed module imports and brought the headline number down. That compression, however, was not a reduction in physical dependency, it was a reclassification of it.

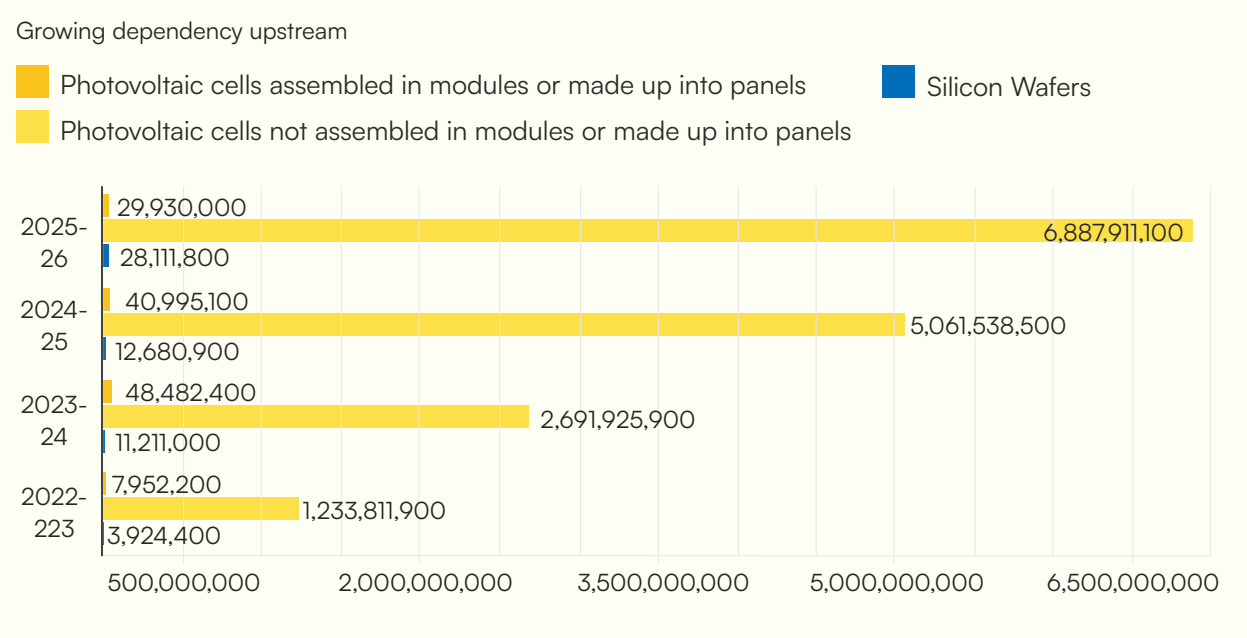
More instructive still is what the data shows about China's role when read in volume rather than value terms. In value terms, China's share of India's total upstream solar import bill appears to have broadly stabilised moving from 66.94% in FY23 to 67% in FY26, with a spike to 81% in FY25. This might suggest limited diversification. The volume data tells a structurally different story.

Figure 7.1: **India's Total Solar Import Bill**



China's volume share of India's total upstream solar imports rose from 57% in FY23 to 78% in FY26, touching 90% at its FY25 peak. The apparent stability in value share between FY23 and FY26 is therefore a price effect, not a supply chain effect. Between FY25 and FY26 alone, China's rupee receipts from India fell by 22% while the physical volume it shipped to India rose by 17%. China is consolidating its physical grip on India's solar supply chain precisely as the value figures make it appear to be loosening. This is the price illusion operating at the aggregate level and it is the most important reason why value-based trade metrics systematically understate the depth of India's upstream exposure.

Figure 7.2: India's Direct Solar Imports



Source: DGFT Trade Data; Unit in nos

India's policy response to this dependency has centred on the Approved List of Models and Manufacturers (ALMM) a government registry maintained by the Ministry of New and Renewable Energy that makes eligibility for publicly funded solar projects conditional on using equipment from listed domestic manufacturers. In practice, any developer seeking a government contract, subsidy, or grid connection under a public scheme must source modules, and increasingly cells, only from manufacturers on the ALMM list; a list on which no foreign manufacturer has ever appeared. The framework was established through an MNRE Order in January 2019, with the first list of approved module manufacturers published in March 2021. After a one-year suspension in FY2023-24 to ease supply chain pressures, the mandate was fully reinstated from April 2024. ALMM-II, notified by MNRE in December 2024 and coming into force from June 2026, extends the same logic one level up the value chain requiring that the cells used in government-backed projects also come from domestically registered manufacturers.

In April 2022, India imposed a 40% Basic Customs Duty on imported modules. In April 2024, it reimposed ALMM, requiring only domestically manufactured modules for government-backed projects. The trade data reflects the impact of these policy changes. Module imports fell from a peak of ₹36,134 crore in FY24, which in itself is a surge driven by developers front-loading imports before the ALMM window closed, to just ₹6,675 crore in FY26. That is an 82% collapse in two years. India's domestic module capacity has expanded with ALMM-listed module capacity exceeding 120 GW by mid-2025, far exceeding annual installation demand of approximately 40—50 GW. India clearly possesses enormous module assembly capability, but what it critically lacks is the cells to feed those factories. India's cell capacity was only about 29 GW by mid-2025, and its domestic module manufacturers must import large quantities of cells from China to sustain production. The result is a structural paradox: India has built a world-class downstream industry on an upstream foundation that remains almost entirely foreign[76].

This is precisely what the cell imports data shows. As modules collapsed, cells surged. India's cell import bill rose from ₹10,648 crore in FY23 to ₹22,021 crore in FY26 which is more than doubling. In the first half of 2025, India's cell imports almost doubled compared to the same period the previous year, increasing from 11 GW to 21 GW, accounting for 52% of the growth in Chinese cell exports globally[77]. India is now, effectively, the single largest buyer of Chinese solar cells in the world.

The pattern is increasingly visible, and policy has masked what is visible at the finished product level. The dependency has simply retreated to the stage before it; cells, and above cells, wafers. **India does not have the same import restrictions on wafer and polysilicon imports as it does for solar cells and modules, and this combined with restrictions on modules under ALMM has created an industrial structure dependent on imported upstream inputs[78].**

The Price Illusion

India's cell import bill appears, at ₹22,021 crore in FY26, to be manageable, roughly double what it was in FY23. However, this value-based reading obscures a volume rise of an entirely different magnitude.

Solar Cells (85414200) - Value vs. Volume, FY23—FY26

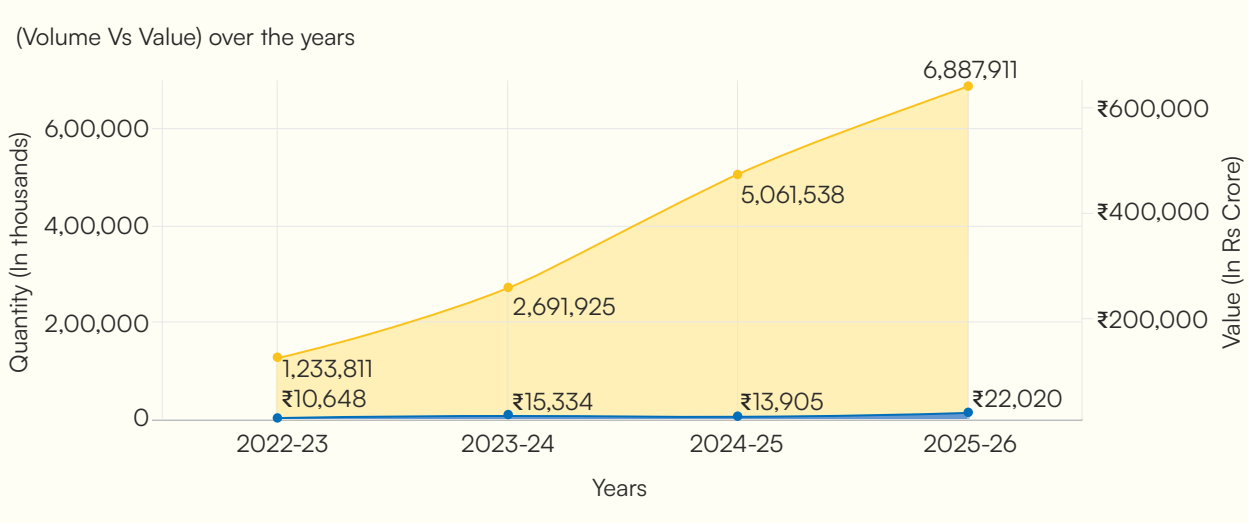
Year	Import Value (₹ Crore)	Import Volume (Billion Units)	Unit Price (₹/cell)
FY23	10648	1.23	₹86.30/unit
FY24	15335	2.69	₹56.97/unit
FY25	13905	5.06	₹27.47
FY26	22021	6.89	₹31.97
Change FY23-FY26	**+107%**	**+458%**	**-63%**

Source: DGFT Trade data (HS 85414200, World row), authors' calculation.

The table above clearly reveals India's growing cell imports in volumes. If cell prices remained at FY23 levels, India's FY26 cell import bill would have been approximately **₹59,445 crore instead** of ₹22,021 crore. India has been importing at a discount that conceals the true volumetric scale of its dependency. The 6.89 billion cells imported in FY26 represent a physical quantity of components whose full cost, at pre-oversupply prices, would have been 2.7 times the recorded import value.

The data also shows that this discount is now slowly reversing. The unit price recovery in FY26 , which is the first upward movement in three consecutive years of decline signals that the floor may have been reached. Prices of Chinese solar products have stabilised since late 2024, amid intensifying industry and government efforts to maintain profitability[79]. India's Directorate General of Trade Remedies issued its Final Findings in September 2025 recommending anti-dumping duties of up to 30% for three years on Chinese solar cells; the Ministry of Finance decides whether to levy them[80]. If those duties are imposed on top of already-recovering base prices, the cell import bill which is recorded at ₹22,021 crore in FY26 at what may prove to be near-historic-low per-unit prices could rise sharply, precisely when India's module factories remain most dependent on imported cell supply.

Figure 7.3: **Import of Unassembled PV Cells**



Data Source: DGFT Trade data

The same volume-versus-value divergence runs through silicon wafers as well. **India's imports of undiffused silicon wafer material grew 7.2 times by weight between FY23 and FY26** from 3,924 tonnes to 28,112 tonnes while import value grew only 83%. The price per kilogram fell from ₹4,016 in FY23 to ₹1,023 in FY26 which is a 74% collapse. The same Chinese oversupply that destroyed cell prices worked its way upstream through the wafer and polysilicon markets. Unlike cells, where FY26 showed the first price recovery (+16%), wafer prices fell a further 2% in FY26, suggesting the upstream price floor has not yet been reached. India is accumulating a silicon material dependency that is growing faster volumetrically than its cell dependency and doing so at prices that, when they normalise, will materially change the cost structure of every domestic cell manufacturer that depends on imported feedstock.

Figure 7.4: **Silicon Wafers Imports**



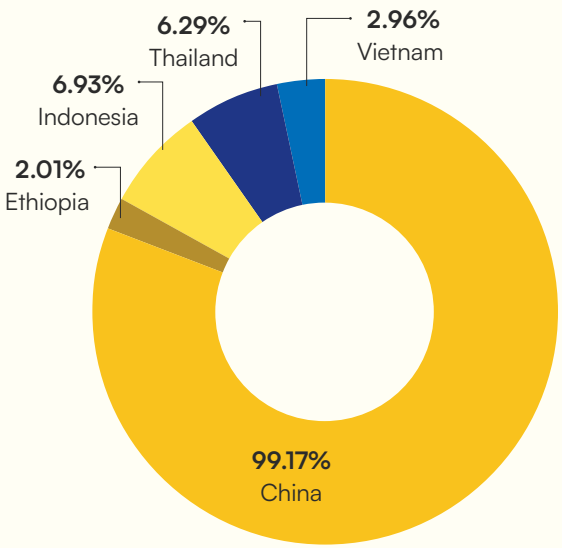
Data Source: DGFT Trade data

The Concentration Risk

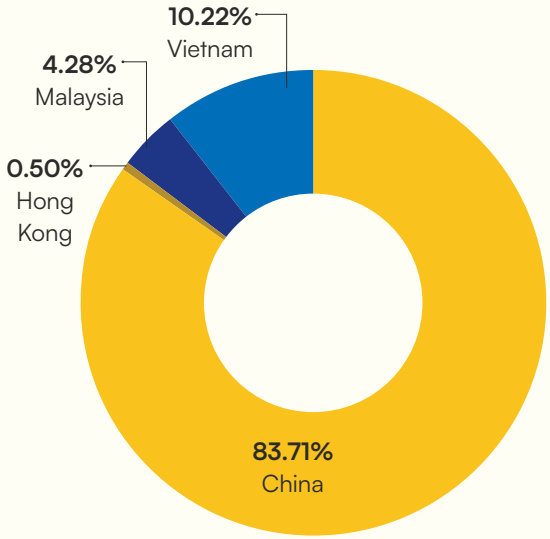
The source country data of solar components reveals a dependency structure that approaches single-source exposure at every level of the solar value chain. The graphs below depict Import shares from countries for silicon wafers; cells not assembled into modules and cells assembled into modules.

Figure 7.5

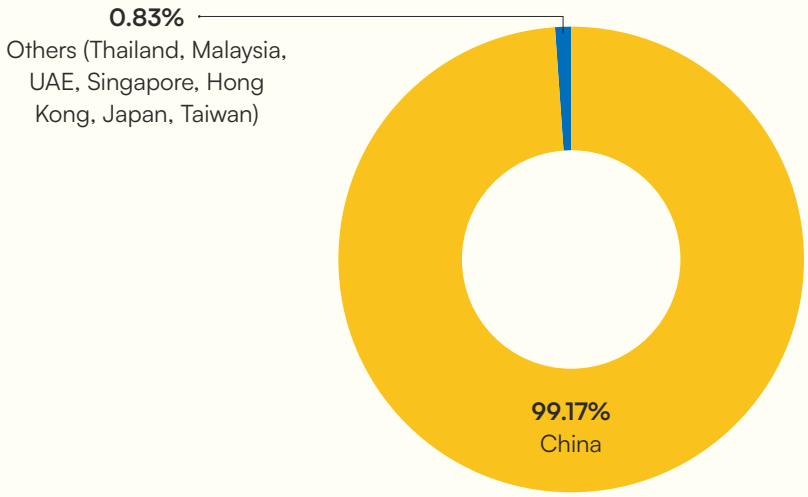
Country-wise Share of Photovoltaic Cell Imports to India (Unassembled & Unpanelled) (2025-26)



Country-wise Share of Photovoltaic Cell Imports to India (Assembled & Panelled) (2025-26)



India's Imports of Silicon Wafers by Source Country (2025-26)



The dependency on wafers which is almost entirely on one country is worrying. China supplies 98—99% of India's silicon wafer imports every year since FY23 in both value and volume terms. This is not market concentration but it is a structural monopoly. The IEA has documented exactly why: China's share in all the key manufacturing stages of solar panels exceeds 80%, and for key elements including polysilicon and wafers, this is set to rise to more than 95% in the coming years based on current manufacturing capacity under construction[81]. For wafers specifically, China has very little competition at the global level[82]. India is not an outlier in this dependency but it is a reflection of a global structural reality.

For cells, the apparent diversification in India's FY26 data Indonesia and Ethiopia appearing as new sources deserves mention. The FY24 cell import data shows Malaysia at 16.8% of India's imports, Cambodia at 6.5%, and Thailand at 13.4%. These Southeast Asian suppliers however do not represent a true supply chain diversification: India also sources from Southeast Asian partners such as Vietnam and Malaysia, but these countries often rely on Chinese raw materials like polysilicon and wafers, reinforcing the underlying dependency[83]. This is a pattern the IEA flagged explicitly: many of the manufacturing units in Southeast Asia are owned by Chinese corporations and serve as offshore production hubs. Therefore, replacing China with Vietnam or Cambodia on the customs declaration does not change who makes the wafers, who controls the cell production technology, or who holds the supply chain leverage.

THE UPSTREAM TRAP: WHY ALMM-II DOES NOT RESOLVE THIS

The policy response to cell dependency is well-designed in concept. ALMM List-II, effective from June 2026, will require all eligible solar projects to use modules built with domestically manufactured cells, which is the same instrument that successfully compressed module imports, now applied one level up the value chain. While this is a step in the right direction, it also encounters a structural constraint that ALMM for modules did not face.

India's domestic cell manufacturers themselves depend on imported wafers, and wafer production depends on imported polysilicon. India's DCR rules specify that crystalline-silicon cells count as locally made only if produced using undiffused silicon wafers and hence cells from imported diffused wafers do not qualify[84]. India currently has only one ingot-wafer facility worth noting which is the 2 GW plant commissioned in 2025 against a projected cell capacity of 65 GW by 2030[85]. Until ALMM List-III for wafers arrives in 2028, and until polysilicon localisation follows, India's cell manufacturers will be assembling domestically labelled cells from Chinese wafers cut from Chinese polysilicon. The dependency retreats upstream at each policy intervention rather than being resolved. Polysilicon and wafer facilities are more expensive, more complex, and slower to build than module or cell facilities[86].

What the wafer data cannot show directly is the layer beneath it. India has no commercial polysilicon production which is the raw feedstock from which every wafer is grown making India a major solar manufacturing nation building scale without sufficient upstream material anchor. Polysilicon represents approximately 32% of ingot and wafer manufacturing costs, which means the cost floor for every domestically manufactured cell is set not in India but in China. The government has announced plans to build 40 GW of wafer capacity by 2027 alongside eventual domestic polysilicon production, but until that

materialises, ALMM-II's mandate faces a structural ceiling: it can require that cells be assembled in India, but it cannot require that the silicon they are made from comes from anywhere other than the one country that produces nearly all of it.

THE SILVER PROBLEM INSIDE THE CELL PROBLEM

There is a second dependency embedded within the first that the rupee figures do not capture. Silver constitutes less than 0.1% of a solar module's weight, but it is the electrically conductive metallisation layer through which all generated power flows and over 80% of India's silver is imported[87]. The exposure is about to intensify since India's manufacturers are pivoting rapidly to TOPCon cell architecture, which is more efficient than PERC, but also more silver-intensive. The shift to n-type high-efficiency technologies including TOPCon has significantly increased demand for silver paste[88]. India is adopting the most silver-hungry cell architecture available precisely as silver markets run persistent deficits and the global shortfall reached an estimated 230 million ounces in 2025 alone[89]. Every imported cell already embeds silver paid for indirectly in its price. Every domestically manufactured cell adds a fresh silver import requirement on top. The silver inside India's solar supply chain is an invisible import within the visible one, growing in both quantity and cost and it will not appear in any customs data until prices force it into view.

THE CIRCULAR BRIDGE: IMPORTS TODAY ARE FEEDSTOCK TOMORROW

Circularity in solar can truly shift this dependency into an enormous opportunity. Everything described so far has been about what India depends on today. The circular argument is about what India can own tomorrow.

The discarded modules from solar PV installations include minerals such as silicon, copper, tellurium, and cadmium, which have been classified as critical minerals for India by the Ministry of Mines. Recycling solar waste to recover these materials will reduce import dependency and enhance India's mineral security. The 6.89 billion cells imported in FY26 alone, assembled into modules and installed across India's solar parks, will begin reaching end-of-life in the 2043—2055 window. They contain silicon, silver, copper, aluminium exactly the materials whose import dependency the preceding analysis has documented. Whether India treats that retiring stock as waste to be stored, or as a domestic material reserve to be recovered, depends entirely on the infrastructure decisions made now, while the installation wave is still building.

The most immediate opportunity is not at end-of-life, but it is on the factory floor, today. India's wafer manufacturing base, though nascent, is being commissioned right now. Silicon kerf or the pure silicon dust lost as waste during wafer cutting represents approximately 32% of polysilicon feed that currently flows into factory wastewater, unrecovered[90]. At India's growing wafer manufacturing scale, kerf recovery infrastructure embedded at the point of commissioning costs a fraction of retrofitting it later, and every kilogram recovered is a kilogram of polysilicon not imported from a supplier whose market share sits at 95% globally and 98% in India's own import data. This is not future-oriented circular thinking, but it is present-tense industrial logic.

The longer-range circular argument is equally compelling. The import data documents a dependency that is accelerating in volume even as it moderates in price. If those volumes are allowed to accumulate without building recovery infrastructure, India will face in 2040, 2045, 2050 a choice between two expensive options: import replacement materials from China again, or scramble to build the recycling systems it should have established two decades earlier. The countries and companies that are building those systems now such as ROSI Solar in France, the US manufacturers achieving 85% silicon waste recycling, the European facilities approaching 90%+ silver recovery will not wait for India to catch up.

GTRI estimates that meeting India's 500 GW renewable target could push the country's total solar equipment import bill to $30 billion annually by 2030[91]. **Against a current direct upstream bill of ₹31,572 crore across just the three core HS codes analysed here, that projection implies an 8× escalation in less than five years if upstream manufacturing does not scale and prices normalise. No manufacturing policy alone closes that gap on that timeline. Domestic recycling of the silicon, silver, and aluminium embedded in panels already in the ground is the one lever that reduces the import exposure from the other direction simultaneously, recovering value from what has already been paid for, while reducing the volume of what must be bought next.**

The energy transition has already traded one form of import dependence for another. The circularity imperative in solar is the strategy that begins to resolve that trade-off from both ends recovering the value embedded in what was already imported, and reducing the upstream exposure on what will be imported next.

6.3 KEY CIRCULAR INTERVENTION AREAS

Solar PV circular economy — key intervention areas

Area	Sub-intervention	Current state in India	Key mechanism / action
A. Upstream manufacturing			
Upstream manufacturing	Kerf loss & silicon recovery	~40% of silicon lost as kerf dust during wafer slicing; ~32% of virgin polysilicon ends as scrap or kerf in wastewater. Effectively zero industry recycling today. **Scale:** Gujarat hosts ~45% of India's module capacity and ~33% of cell capacity.	Embed press filtration + silicon recovery in wafer-cutting lines at gigawatt-scale fabs (Gujarat cluster). Pair with end-of-life recycling for up to **80% reduction** in PV-grade silicon carbon emissions. Recovered kerf can supply feedstock for steel, chemicals, or battery anode production which is a direct solar-battery circular synergy.

Area	Sub-intervention	Current state in India	Key mechanism / action
Upstream manufacturing	Silver recovery & substitution	Silver <0.1% by weight but ~47% of recoverable module value. India imports >70% of silver (~7,000 t in FY2023, ₹54,000 cr). TOPCon dominant upcoming cell architecture uses 29—80% more silver than PERC. **Risk:** TOPCon projected to exceed 58% of India's module capacity and 64% of cell capacity by 2027.	Deploy hydrometallurgical + electrochemical recovery (base-activated persulfate leaching + electrodeposition). Lab-proven **98.7% silver recovery efficiency.** Integrate into manufacturing scrap loops and end-of-life pipelines to reduce strategic import dependence.
B. Module design			
Module design	Design for disassembly (DfD)	EVA encapsulant bonds cells firmly to glass in a laminated structure. Separation requires thermal, chemical, or mechanical delamination — destructive and energy-intensive. Second-life assessment near-impossible.	Mandate DfD standards for new modules entering India's market — mechanical fastening, modular cell units, non-adhesive encapsulants. Align with PLI scheme conditions and BWMR / EPR targets. Enables future high-value recovery of silicon, silver, copper, and tin.
	Longer-lifespan design	Up to 1-in-5 modules degrade 1.5× faster than average, creating premature waste. Indian conditions (UV, thermal cycling, dust, monsoon humidity) not reflected in standard testing regimes.	Establish India-specific accelerated degradation testing under MNRE. Mandate anti-soiling coatings, bifacial structures, and higher-grade encapsulants. Extends replacement cycles, reduces raw material demand, and limits early-loss repowering waste.
C. Manufacturing ecosystems (industrial symbiosis)			
Industrial symbiosis	Co-located recycling & cross-sector flows	No industrial-scale PV recycling facility in India as of 2025. Gujarat cluster (45% of module capacity) is geographically concentrated but lacks co-located recycling infrastructure.	Site India's first industrial PV recycling plant within or adjacent to Gujarat cluster. Eliminates reverse logistics — the largest single cost barrier for recycling and provides stable, predictable in-process scrap as feedstock. **Cross-sector flows:** kerf → battery anodes / metallurgical silicon; recovered silver → electronics; aluminium frames → secondary smelters.

Area	Sub-intervention	Current state in India	Key mechanism / action
D. End-of-life integration			
End-of-life pipeline	Formal collection systems	Formal EoL management ecosystem effectively non-existent. E-Waste Rules 2022 mandate storage until 2034—35, providing a policy window. Modules are large, heavy, and geographically dispersed across a heterogeneous owner base. **Window:** ~10 years before the first mass retirement wave.	Build state-level aggregation nodes and transport infrastructure for large, fragile glass-based panels. Assign clear EPR obligations to producers. Use the 2034—35 storage deadline as a forcing function for investment.
	High-value recycling technology	340 kt estimated solar waste by 2030, containing ~10 kt silicon, 12—18 t silver, and 16 t cadmium & tellurium - mostly classified as critical minerals by India's Ministry of Mines. No domestic high-value recovery technology at scale.	Commission IITs / CSIR labs to adapt high-value recovery processes to India's material streams, targeting >90% recovery of silicon, silver, copper, and tin. Reduces critical mineral import dependence and addresses the 340 kt+ waste wave projected by 2030.

A Upstream Manufacturing: Closing the Resource Loop Before the Module Leaves the Factory

The most economically tractable circular interventions in solar PV manufacturing occur upstream in the fab itself where material waste streams are concentrated, well-characterised, and accessible. Unlike end-of-life recycling, upstream recovery does not require reverse logistics and can be directly integrated into production cost accounting.

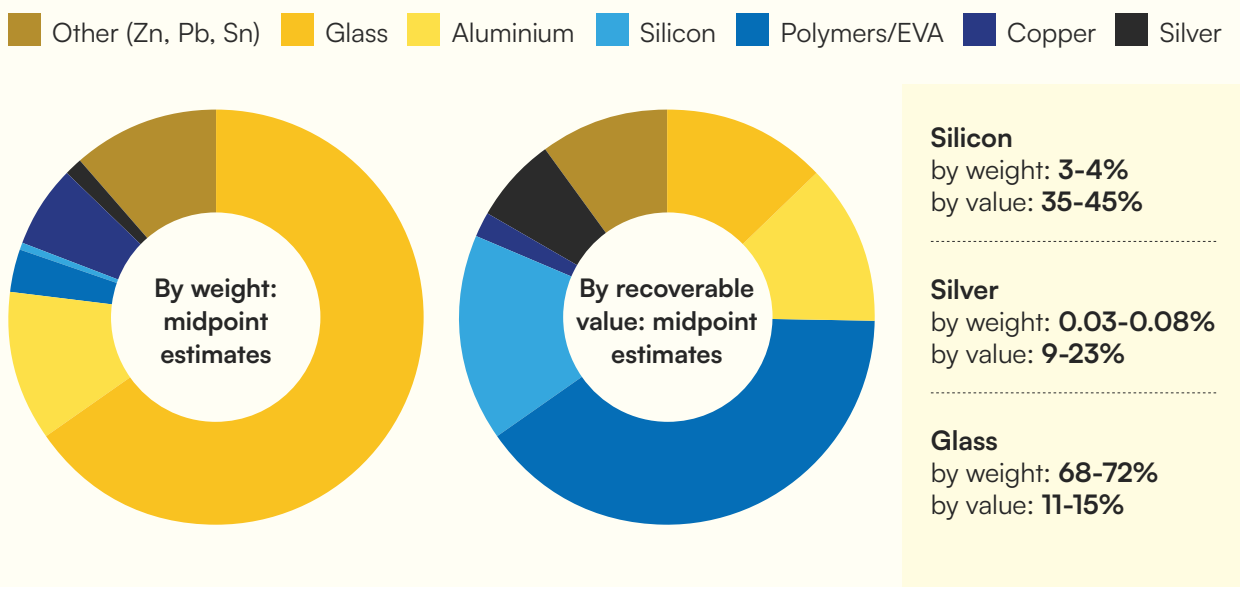
Kerf loss reduction and silicon recovery: The production of silicon wafers for solar cells involves sawing silicon ingots into very thin slices which is a process that generates a significant quantity of silicon dust, known as kerf, suspended in the sawing slurry. When cutting silicon ingots into very thin wafers, the PV industry currently loses approximately 40% of the material as silicon dust mixed with the sawing liquid. This sludge, called kerf, is composed of highly pure silicon particles but is currently not recycled by the industry[92]. This is not a marginal waste stream: about 68% of the virgin polysilicon feed is transformed into wafers while the rest 32% ends up as dust, or silicon kerf loss in industrial wastewater.

At India's current and projected manufacturing scale this represents an enormous recoverable resource. A silicon recycling infrastructure based on kerf recovery, combined with end-of-life module recycling, could reduce the carbon emissions of PV-grade silicon production by up to 80%[93]. For India's gigawatt-scale manufacturers in states like Gujarat, embedding press filtration and silicon recovery systems in their wafer-cutting lines represents a high-return, near-term circular investment with immediate cost reduction potential.

The strategic case for prioritising kerf recovery now also rests on a convergence of timing, geography, and industrial logic that will not recur easily. India's ingot and wafer manufacturing base is being commissioned at this moment. As of June 2025, India's installed wafer capacity stood at 5.3 GW, with ALMM List-III for wafers coming into force in 2028, providing a regulatory anchor for mandating kerf recovery standards at new facilities[94]. Embedding recovery infrastructure now, at the point of construction, costs a fraction of retrofitting later. The on-site nature of the waste stream is the decisive advantage: unlike end-of-life module recycling, which requires reverse logistics, collection networks, and disassembly of weathered multi-layer structures, kerf is generated on the factory floor in a controlled, wet-processed environment with no collection system required, no fragmented ownership problem, and no need for reverse logistics design. Given that polysilicon represents approximately 32% of ingot and wafer manufacturing costs, and that India currently imports polysilicon at close to 100% from China[95], every kilogram of silicon recovered on-site is a kilogram not imported and this is a direct and immediate cost reduction, not a future circular economy aspiration.

Silver recovery and substitution: Silver is perhaps the most economically significant material in a solar PV module. Even though Glass dominates by mass at 68—72%, it contributes only 11—15% of recoverable material value. Silicon at just 3—4% by weight accounts for 35—45% of value, while silver, at less than 0.1% by weight, contributes a further 9—23%. Together, silicon and silver represent the primary economic drivers of end-of-life recycling[96].

Figure 7.6: **Weight vs. recoverable value: the silicon and silver paradox in crystalline silicon PV modules**



Source: IEA, Special Report on Solar PV Global Supply Chains (2022), Figure on p.21. IEA report gives ranges; midpoints used here. Value-based shares calculated using 2021 average market prices: silver USD 803/kg; copper USD 9,408/Mt; silicon USD 34/kg; aluminium USD 2,500/Mt; glass USD 590/Mt. IEA sources material composition estimates from Soren (2022), Frischknecht et al. (2020), Carrara et al. (2020) and others.

This creates both an opportunity and an urgency. Silver's strategic importance for India is acute: India produced approximately 794 tonnes of silver in 2022—23, overwhelmingly as a by-product of lead, zinc, and copper refining, and is among the world's top five silver consumers. Over 8,156 tonnes of silver were imported in 2022—23 at a value of approximately ₹4,22,371 crore[97].

The global PV industry could account for up to 40% of global silver demand by 2030, with new c-Si designs such as TOPCon and SHJ driving up silver demand significantly TOPCon requiring 29—80% more silver than PERC, and SHJ requiring more than double that of PERC[98]. This is directly relevant to India because TOPCon modules are anticipated to account for more than 58% of India's annual module production capacity and over 64% of cell production capacity by 2027. **India's technology trajectory is thus moving precisely toward the most silver-intensive cell architectures at exactly the moment when global silver supply constraints are intensifying.** On the recovery side, science is advancing rapidly. Researchers have developed novel hydrometallurgical and electrochemical processes to recover pure silver from solar cells, achieving a recovery efficiency of 98.7% using a combined base-activated persulfate leaching followed by electrodeposition-redox replacement which is a technique that is selective for silver recovery and does not require additional chemical additions[99].

The global PV industry could account for up to 40% of global silver demand by 2030, with new c-Si designs such as TOPCon and SHJ driving up silver demand significantly TOPCon requiring 29—80% more silver than PERC, and SHJ requiring more than double that of PERC.

B Module Design: Engineering for the Second Life

The design decisions made today for modules entering India's growing installed base will determine the ease and economics of recycling 20—30 years from now. There is a structural tension in current module design: manufacturing optimisations that improve performance and reduce production costs such as integrated encapsulants, frameless designs, and adhesive cell bonding simultaneously make end-of-life disassembly more difficult and energy-intensive.

Design for Disassembly (DfD). A standard crystalline silicon module consists of: a glass front layer; ethylene vinyl acetate (EVA) encapsulant; silicon cells with silver metallisation; a rear encapsulant and backsheet; and an aluminium frame. The challenge is that the EVA encapsulant bonds the cells firmly to the glass in a laminated structure that requires either thermal, chemical, or mechanical delamination to separate. The complete recycling process for silicon-based PV panels can be summarised into two main sections: disassembly and delamination treatment through physical, thermal, and chemical means, and the retrieval of valuable metals including silicon, silver, copper, and tin[100].

Longer-lifespan module design. Research from the University of New South Wales has found that up to one-fifth of solar PV modules degrade 1.5 times faster than average[101], creating premature end-of-life waste or the "early loss" scenario that significantly inflates waste projections. For India, where modules experience

intense UV radiation, thermal cycling, dust accumulation, and monsoon humidity stress conditions distinct from those in temperate testing environments there is a specific need for accelerated degradation testing under Indian climatic conditions before setting module lifespan assumptions for waste management planning. Longer lifespan modules reduce both raw material demand by extending time between replacement cycles and waste generation. Designing modules with anti-soiling coatings, bifacial structures, and higher quality encapsulants not only improves energy yield but reduces the frequency of repowering which is an emerging source of "early loss" waste[102].

C Manufacturing Ecosystems: Industrial Symbiosis and Co-location

The single most powerful structural intervention for making India's solar manufacturing circular is geography. Designing manufacturing parks such that waste streams from one facility become feedstocks for another is the principle of industrial symbiosis, and India's highly concentrated solar manufacturing geography provides an exceptional platform for it.

Co-located recycling facilities: Gujarat's solar manufacturing cluster hosting approximately 45% of India's module capacity and over a third of cell capacity is already the natural location for India's first industrial-scale solar PV recycling facility. Co-locating a recycling plant within or adjacent to a manufacturing cluster eliminates reverse logistics costs which is the largest single cost barrier for recycling and provides a stable, predictable feedstock of in-process manufacturing scrap in good material condition making it easier to process.

Beyond PV-specific recycling, India's solar manufacturing hubs can be designed as broader industrial symbiosis ecosystems where material and energy flows are exchanged between sectors. Silicon kerf recovered from wafer production can supply metallurgical silicon inputs for the steel and chemical industries or serve as anode precursor material for battery manufacturers which is a direct circular synergy between India's solar and battery manufacturing ambitions. Recovered silver can be refined and reused in electronics. Aluminium frames from decommissioned modules are highly recyclable and can enter aluminium smelters' secondary feedstock.

D End-of-Life Integration: Building the Formal Pipeline

The formal end-of-life management ecosystem for solar PV in India is, as of 2025, effectively non-existent. This is not yet a crisis since the waste volumes are manageable, and the E-Waste Rules 2022's mandated storage period until 2034—35 provides a policy window within which to build the necessary infrastructure. The question is whether India uses this window proactively or stumbles into a crisis when the first wave of mass-deployed modules begins retiring in the early 2030s.

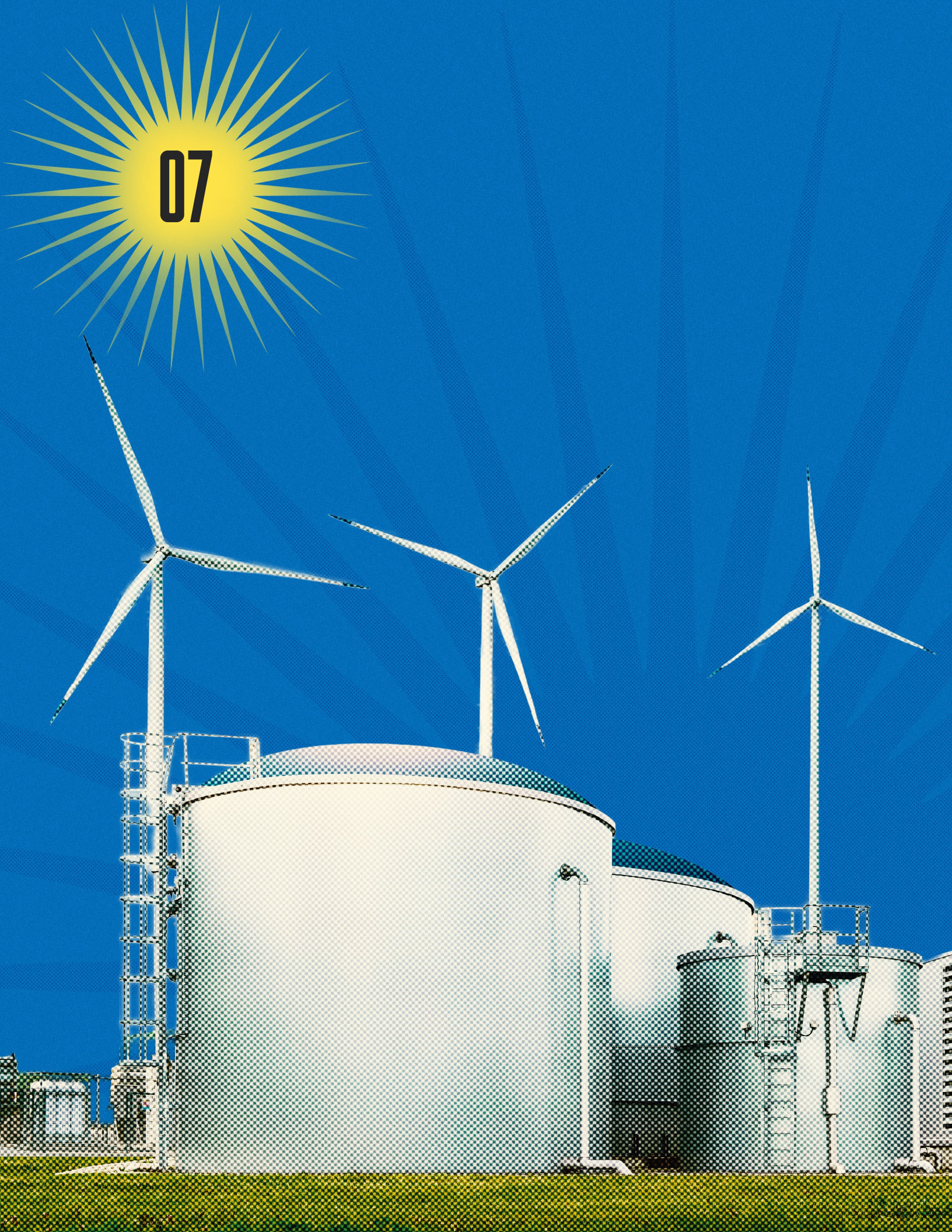
Formal collection systems: The challenge of collection for solar waste differs fundamentally from most other e-waste categories. Modules are large, heavy and geographically dispersed across utility-scale parks, and owned by a heterogeneous mix of utilities, commercial buyers, and households. Designing a collection system requires state-level aggregation nodes, transport infrastructure capable of handling large fragile glass-based panels, and clear EPR obligations that assign collection responsibility to producers.

High-value recycling: End-of-life crystalline silicon modules contain a recoverable materials inventory whose economic value India cannot afford to squander. The 340 kt of solar waste estimated to exist in

India by 2030 containing about 10 kilotonnes of silicon, 12—18 tonnes of silver, and 16 tonnes of cadmium and tellurium the majority of which have been classified as critical minerals by India's Ministry of Mines. Therefore, recycling solar module waste by 2047 could address India's demand for silicon, aluminium etc and reduce its import dependence significantly. The technology for high-value recovery is maturing globally. An innovative high-value-recovery recycling technology for crystalline silicon PV modules developed by the French company ROSI has reached Technology Readiness Level 8 and been deployed at an industrial plant in France since May 2023. Life cycle assessment of this process shows significant environmental benefits across 9 out of 14 impact categories, with over 90% impact reduction[103]. India's R&D institutions such as IITs, CSIR labs, and MNRE-funded centres are well-positioned to adapt such technologies to India's specific material streams.



07



WIND – CIRCULAR MANUFACTURING PATHWAYS FOR INDIA

Current State

India's wind energy sector stands on considerably stronger manufacturing foundations than its solar or battery counterparts, but it is heading toward a massive waste challenge it has barely begun to plan for. India is today the world's third-largest wind manufacturing base and ranks fourth globally in cumulative installed wind capacity, with around 55 GW operational, and has a domestic manufacturing capacity of approximately 20 GW annually which is sufficient to meet about 10% of global demand[104]. This is an impressive industrial achievement, built over three decades through the presence of global OEMs, alongside a growing ecosystem of domestic component suppliers. India's annual wind turbine manufacturing capacity stands at around 20 GW compared to domestic demand of 7—8 GW per year. The country has 15 manufacturers offering 31 turbine models ranging from 225 kW to 5.3 MW in operation[105].

Despite these strengths, there are some significant gaps. Indian-made turbines are estimated to be 30—60% more expensive than their Chinese counterparts, largely due to higher input costs and continued reliance on imported components. Key parts such as special bearings, gearboxes, yaw mechanisms, and turbine controllers are still imported, often from China, which supplies half of India's hub castings and 90% of gearbox castings[106]. The government's ALMM (Wind) mandate which requires hub and nacelle assembly facilities to be located in India and is progressively extending to blades, towers, and gearboxes is designed to deepen this localisation further, but also creates short-term supply pressure.

Unlike the battery and solar sectors, which now have EPR frameworks at various stages of implementation, the wind sector in India has no dedicated circularity or end-of-life policy. The only relevant instrument is MNRE's National Repowering & Life Extension Policy (2023). However, this addresses turbine replacement, not material recovery, and delegates scrap disposal to generic waste management rules with no recycling targets or producer responsibility obligations. Wind turbine components are not yet covered by any specific waste management or producer responsibility regulation. What exists is largely general as wind turbines are subject to standard industrial waste rules when decommissioned, but there is no national framework for blade disposal, no landfill ban, no recycled content mandate, and no EPR mechanism that would assign financial responsibility for end-of-life management to turbine manufacturers. The disposal of outdated components such as control systems, inverters, and batteries is challenging due to their hazardous materials, and wind turbine blades made of composite materials further complicate recycling and contribute to India's growing e-waste issues.

The critical circularity concern in wind is not the metal components but roughly 80—94% of a wind turbine by mass is made up of readily recyclable materials, including steel, copper, aluminium, and iron, for which well-established recycling processes exist[107]. The challenge is concentrated almost entirely in the blades.

Wind turbine blades are large structures made from glass or carbon fibre reinforced with thermosetting resins materials designed to last 20—25 years under extreme mechanical stress. Their very durability is the problem: once the resin hardens during manufacturing, the blade becomes extremely difficult to break apart and recycle. Presently, most wind turbine blade waste is sent to landfill, though this is not environmentally benign, and many EU countries have now forbidden the landfilling of composite waste[108].

Globally, by 2050, wind turbines will produce an estimated 43.4 million tonnes of blade waste[109]. Between 2020 and 2030, many of the wind turbines installed in the early 2000s will reach the end of their useful life. By 2030, wind turbine blades will have accumulated globally at a rate of 100,000 tonnes per annum, rising to 800,000 tonnes per annum by 2050[110].

For India specifically, the first wave of this challenge is now arriving. India has approximately 25 GW worth of turbines under 2 MW capacity that can be repowered or have their operational life extended under the government's December 2023 repowering policy. Most of the wind turbines installed in India up to the year 2000 are sub-MW capacity and are at sites with high wind energy potential, with some having already completed their design life[111]. Repowering these sites will generate a significant stream of decommissioned blades for which India currently has no formal disposal pathway and no recycling infrastructure.

India has approximately 25 GW worth of turbines under 2 MW capacity that can be repowered or have their operational life extended under the government's December 2023 repowering policy.

7.1 QUANTIFYING THE WAVE: INDIA'S WIND BLADE WASTE IN NUMBERS

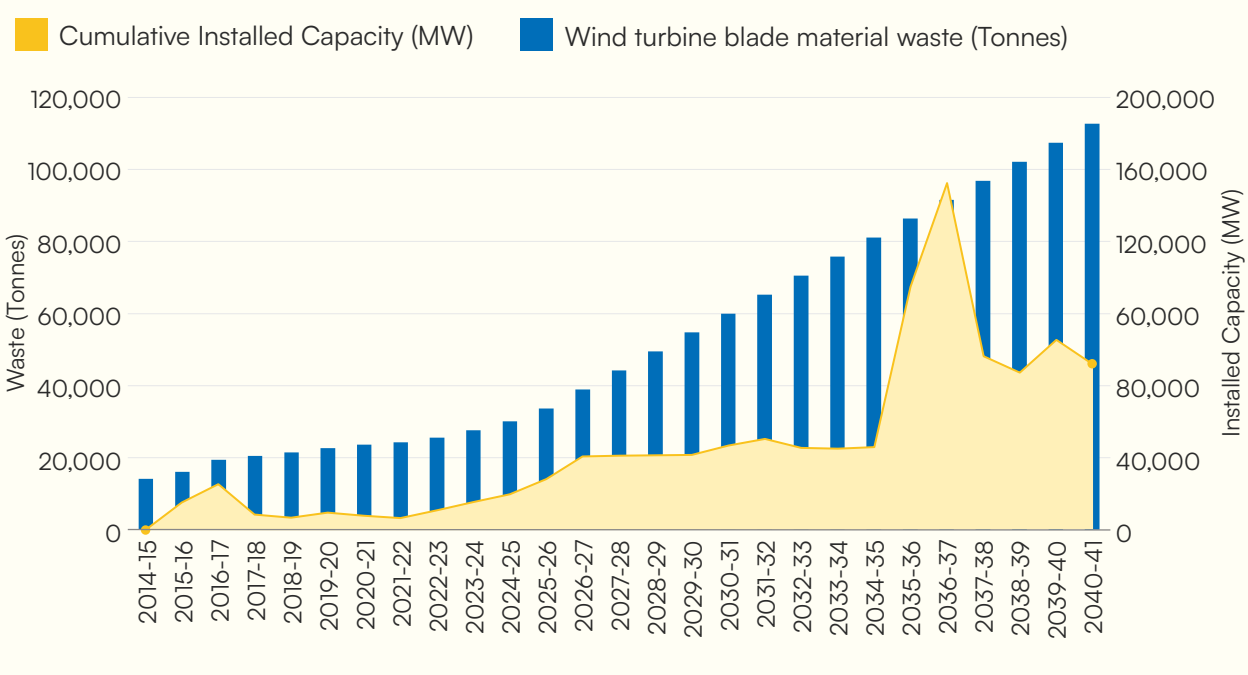
It is now evident that blade waste is a key concern in the wind energy sector mainly due to the intractable chemistry of thermoset composites, the absence of any regulatory framework and how the logic of cement co-processing can be a near-term route out. To plan for circularity however, it is important to understand in the Indian context- **How much blade waste is actually coming, when, and where?**

To answer this, we developed an original projection calibrated to India's installed capacity data, combining the cohort-based methodology of **Liu and Barlow (2017)[112] and Heng et al. (2021)[113]** with India-specific capacity trajectory assumptions from the GWEC India Wind Report 2025[114]. Blade mass is estimated at 13.41 tonnes per MW; the value corresponding to the 2—5 MW turbine class that now represents the bulk of India's installed and near-term pipeline. Waste is released over the blade lifecycle in three tranches: 17.2% in the manufacturing year, 1.1% in the sixth service year, and the full remaining blade mass at decommissioning in the 21st year. A full methodological description is provided in the Appendix.

The results tell a story in three distinct phases.

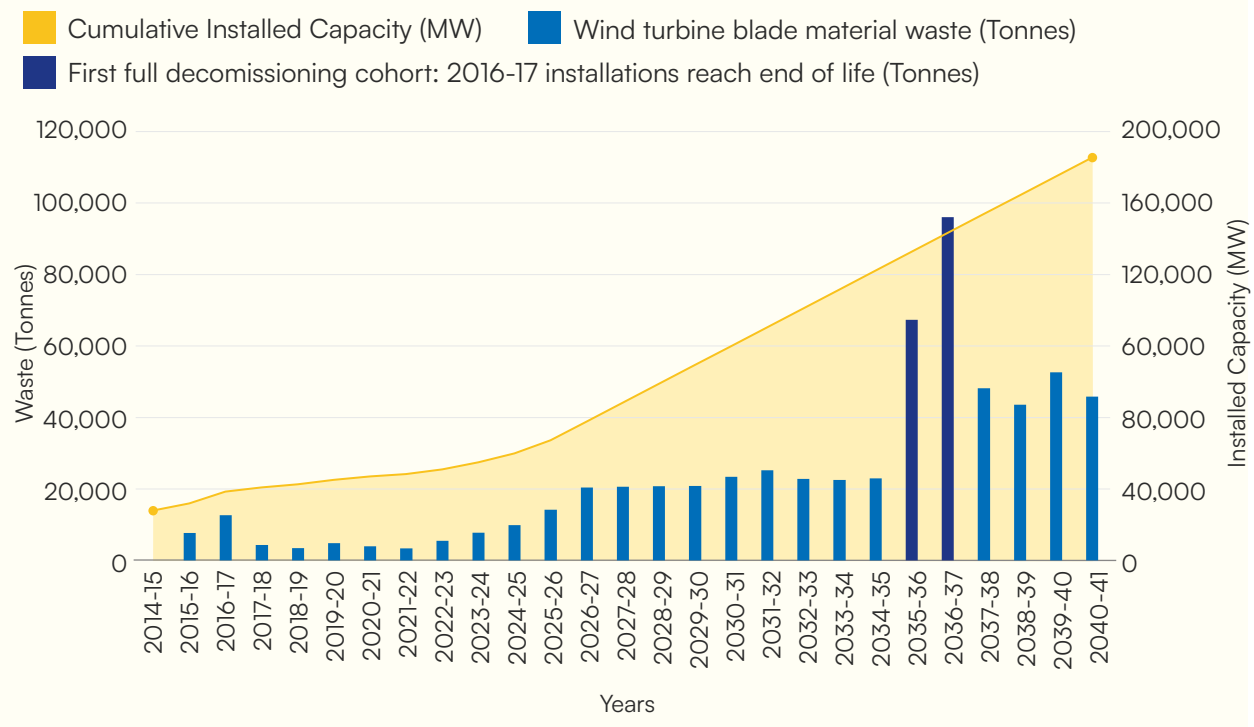
The near-term accumulation phase, which is between 2025 and 2034, is already underway and growing. India generated 9,883 tonnes of blade waste in 2024-25 from wind capacity added after 2014-15, which is the base year of this projection as the country ramps up annual additions to approximately 8.78 GW per year to reach the 100 GW target by 2030, this rises steeply to 14,177 tonnes in 2025-26, then approximately 20,000—25,000 tonnes per year through the early 2030s as each new cohort of installations begins generating its sixth-year service waste and manufacturing scrap. **Over the six-year window from 2025-26 to 2030-31, roughly 120,000 tonnes of blade waste will be generated from new additions alone. There is currently no formal collection infrastructure, no EPR obligation, and no disposal pathway for any of it.**

Figure 8.1: **Cumulative Installed Capacity and Wind Turbine Blade Material Waste (2015-2040)**



The decommissioning spike from 2035 to 2037 is the defining event in the entire projection, and it arrives with very little warning. Annual blade waste more than doubles in a single year: from approximately 22966 tonnes in 2034-35; a figure that has held broadly flat for four years to over 67353 tonnes in 2035-36, as the 2015-16 installation cohort hits its 21st year and decommissions in full. The following year 2036-37 is the peak: 96,050 tonnes in a single year, as the large 2016-17 installation cohort (5.5 GW, the biggest single-year addition in that era) decommissions simultaneously. **The two-years of 2035 and 2036 generates over 163,000 tonnes of blade waste which is more than the entire accumulated total from the previous decade.**

Figure 8.2: **Installed capacity and wind turbine blade waste: the effect of decommisioning**



The post-peak elevated plateau from 2038 onwards stabilises at 43,000—53,000 tonnes per year. These volumes do not represent a return to pre-spike levels, but they represent the new structural floor of India's annual blade waste. Each year of 8.78 GW additions creates a future decommissioning cohort 21 years later, meaning the waste volumes of the late 2030s become the baseline for the 2050s and 2060s if India continues on its capacity expansion trajectory toward 140 GW and beyond. **The decommissioning problem does not resolve after 2037 but it only institutionalises.**

Over the full modelling period from 2015-16 to 2040-41, India will generate a cumulative total of approximately 630,820 tonnes of wind-blade waste from capacity added after 2014. This figure does not include waste from the pre-2014 installed stock of 23 GW, which will add further volumes depending on turbine vintage and decommissioning schedules.

Geographical Distribution of the Blade Waste

India's wind installation is not evenly distributed, and neither is the waste. Gujarat (27.89%), Tamil Nadu (21.65%), Karnataka (15.56%), Maharashtra (10.57%), Rajasthan (9.54%), Andhra Pradesh (7.87%), and Madhya Pradesh (6.56%) together account for over 99% of the country's installed wind base. Using current state shares as the basis for allocating future capacity additions, the waste distribution across states follows the same concentration.

Gujarat carries the largest sustained burden of 6989 tonnes in 2025-26 rising to 25,110 tonnes at the 2036-37 peak, reflecting its dominant share of both existing and future installations. Tamil Nadu, Karnataka, and Andhra Pradesh each face significant volumes, with Andhra Pradesh's peak-year

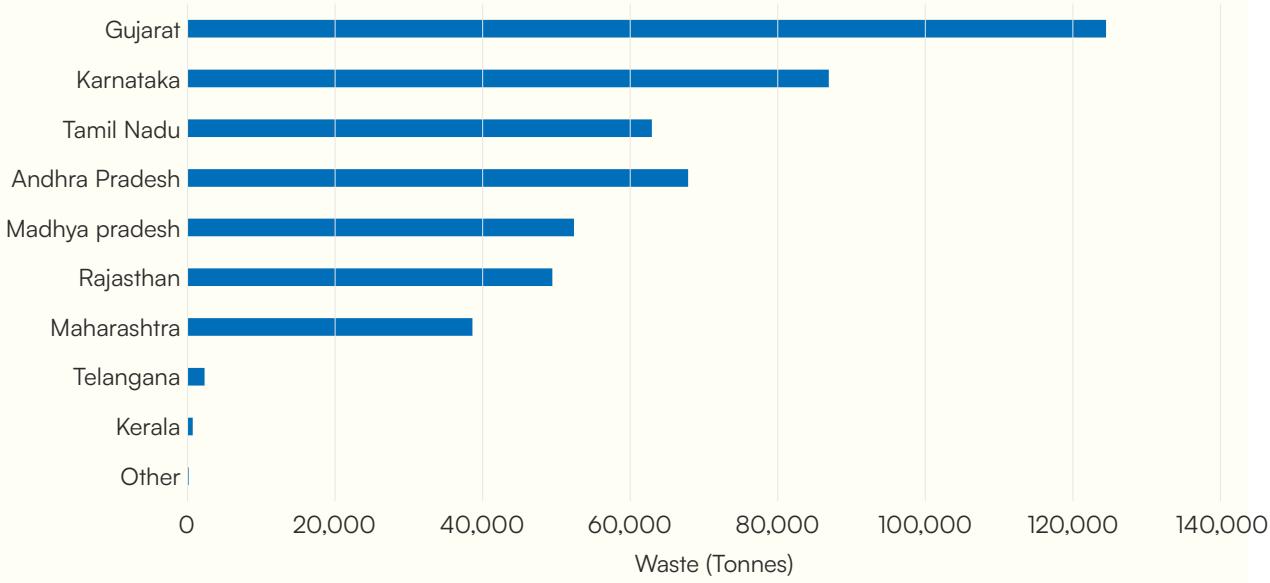
figure (31,030 tonnes in 2036-37, nearly a third of India's national total) driven by the size of the 2016-17 installation cohort decommissioning simultaneously in that state.

The state that deserves special attention in planning terms is Gujarat. It already hosts 45% of India's solar module manufacturing, the largest concentration of wind capacity, and a significant share of upcoming battery manufacturing clusters[115]. The convergence of solar, wind, and battery waste streams in a single state is not a coincidence but it is a consequence of Gujarat's industrial geography, and it creates a structural opportunity for co-located composite and materials recycling infrastructure that serves multiple waste streams simultaneously.

In 2036-37, Andhra Pradesh also produces 31,030 tonnes against Gujarat's 25,110 which is a consequence not of its overall capacity share, which is modest at 7.87%, but of the timing of its buildout. The large 2016-17 installation cohort in AP decommissions all at once, creating a single-year concentration that outstrips even the country's largest wind state.

Crucially, no two major states peak in the same year. Madhya Pradesh and Rajasthan face their worst year in 2035-36; Andhra Pradesh and Karnataka in 2036-37; Tamil Nadu not until 2038-39; and Gujarat last of all, in 2039-40. The national aggregate obscures this staggering. Hence, what looks like a two-year crisis at the all-India level is, beneath the surface, a rolling five-year sequence of state-level peaks. This is less a problem than a planning lever: investments in collection and processing infrastructure can be sequenced by state rather than deployed everywhere simultaneously.

Figure 8.3: **Cumulative Wind Turbine Blade Waste (2015-2036)**



The geographic concentration of the waste stream is, counterintuitively, an advantage. Unlike municipal solid waste which is diffuse, heterogeneous, and difficult to aggregate wind blade waste is physically large, traceable, and temporally foreseeable to within a single year. A turbine installed in 2016 will reach end-of-life in 2037. The planning for this can begin from an early stage.

7.2 KEY CIRCULAR INTERVENTION AREAS

Snapshot— key intervention areas

Area	Sub-intervention	Current state in India	Key mechanism / action
A. Design: building recyclability into the blade			
Blade design	Recyclable resin & material innovation	Conventional blades use thermoset epoxy -irreversibly hardened, impossible to melt and reform. No commercial-scale closed-loop blade recycling exists in India today. **India exposure:** Siemens Gamesa and LM Wind Power both have blade manufacturing operations in India. Adani New Industries is already investing in recyclable materials.	Adopt recyclable epoxy resins (e.g. Siemens Gamesa RecyclableBlade, first deployed commercially 2021). Blade is immersed in mild heated acid to separate fibre, resin, and structural materials for secondary use in automotive and consumer goods. Vestas/CETEC process enables closed-loop recycling - epoxy broken down into raw material reusable in new blades without redesign. ZEBRA consortium (2024) demonstrated 75% recycled resin yield and glass fibre recovery from thermoplastic blades.
	Modular turbine design	Blades approaching 100 m cannot be transported whole on most Indian roads. All end-of-life pathways currently require on-site cutting - costly and unplanned.	Design blades with natural sectional joints or modular assembly to reduce logistical cost and enable selective recycling of segments with different material compositions. Embed decommissioning planning into blade design specifications under PLI scheme conditions and MNRE type-certification requirements.

Area	Sub-intervention	Current state in India	Key mechanism / action
B. Manufacturing: reducing waste before the blade leaves the factory			
Manufacturing waste	Composite scrap minimisation	Each MW of installed wind capacity requires approximately 9.57—13.41 tonnes of composite blade material, of which approximately 25% — around 3.35 t/MW becomes waste across the turbine's lifecycle through manufacturing scrap, service maintenance, and end-of-life decommissioning Manufacturing scrap off-cuts, rejected laminates, trimming waste is generated in concentrated, predictable locations and is easier to manage than end-of-life blades.	Precision cutting, improved mould design, and lean manufacturing processes to reduce scrap. Vestas has set a zero-waste-turbines target by 2040. Indian blade manufacturers serving export markets face growing ESG pressure to demonstrate manufacturing waste reduction. Embed scrap reporting and reduction targets as PLI scheme conditions.
	Alternative & bio-based materials	Conventional blades use balsa wood as core material, raising sustainability concerns given tropical forest sourcing. Bio-based resins are not yet at commercial scale.	LM Wind Power (with operations in India) has minimised balsa by substituting synthetic PET and PVC foam core. India's blade manufacturers can adopt this now. Monitor NREL's PECAN bio-based resin (40% lower GHG than conventional epoxy) for commercial readiness; position domestic R&D institutions to adapt for Indian manufacturing conditions.
C. End-of-life integration: keeping blades out of landfills			
End-of-life pathways	Blade repurposing	No national inventory of decommissioned blades exists. No formal connection between wind developers and state public works departments. Repowering of ~25 GW sub-2 MW turbines will generate a large, predictable supply of composite structures with no planned route.	Structurally repurpose decommissioned blades in rural and peri-urban infrastructure: footbridges over irrigation canals, shade structures at bus stops, noise barriers on the National Highway Network. Build: (1) national decommissioned blade inventory; (2) standardised structural integrity assessment process; (3) formal connection between MNRE repowering policy and state PWD procurement. Use National Infrastructure Pipeline as entry point.

Area	Sub-intervention	Current state in India	Key mechanism / action
End-of-life pathways	Cement co-processing	India has 200+ large cement kilns with existing alternative fuel and raw material (AFR) programmes. No formal blade waste stream is yet integrated. In the US, Vestas co-processed ~300 blades through cement kilns in 2021; GE Renewable Energy has established partnerships with LafargeHolcim and Veolia at commercial scale.	Formalise blade waste co-processing within AFR programmes of Indian cement majors (UltraTech, Ambuja, ACC, Dalmia) in partnership with wind developers and MNRE. 1 tonne of blade waste co-processed reduces cement CO_2 emissions by 110 kg and saves 461 kg of raw materials - a circular contribution, not merely disposal. Scale via MNRE—cement industry MoU tied to repowering programme.

A Design: Building Recyclability Into the Blade

The most durable solution to the blade waste problem is to design blades that can be recycled from the outset. This is not merely aspirational but it is already happening in the global industry, and India's blade manufacturers are well-positioned to adopt and scale these innovations.

Material Innovation: The central design challenge is that conventional blades use materials that harden irreversibly during manufacturing. Once set, they cannot be melted down and reformed, which is why recycling is so difficult. The emerging solution is to substitute these with materials that can be chemically "unzipped" at end-of-life. Siemens Gamesa which has a significant manufacturing presence in India launched the world's first fully recyclable wind turbine blade for commercial offshore use in September 2021. The RecyclableBlade uses a recyclable epoxy resin that can be separated from the fiberglass, plastic, wood, and metals by immersing the blade in a heated mild acidic solution. The process protects the properties of the materials, which can then be recovered and prepared for secondary use including in automotive applications and consumer goods[116].

Going further, Vestas, in partnership with Aarhus University, the Danish Technological Institute, and epoxy manufacturer Olin, developed a chemical process through the CETEC project that allows epoxy-based blades to be broken down into raw material reusable in new wind turbine blades effectively enabling closed-loop recycling without requiring blade redesign[117]. In October 2024, the ZEBRA consortium, featuring Arkema, Owens Corning, LM Wind Power, and SUEZ, successfully demonstrated a closed-loop recycling process for thermoplastic wind turbine blades, recovering recycled resin with a 75% yield and reclaiming glass fibres for integration back into new blade production[118].

These developments are directly relevant to India. Siemens Gamesa and LM Wind Power both have blade manufacturing operations in India. As they adopt recyclable blade designs in their global portfolios, their Indian manufacturing lines will eventually need to follow. India's domestic blade manufacturers, including Adani New Industries ,which is already investing in recyclable materials have the opportunity to embed these design choices early, before large volumes of non-recyclable blades accumulate.

Modular turbine design: Alongside material innovation, turbine architecture that separates the blade into discrete sections rather than a single monolithic structure would significantly reduce the logistical cost and complexity of end-of-life management. Blades approaching 100 metres in length cannot be transported whole on most Indian roads, which means that any end-of-life pathway requires on-site cutting. Designing blades with natural sectional joints or modular assembly would facilitate both transportation and selective recycling of different blade segments, which may have different material compositions and therefore different optimal end-of-life routes.

B Manufacturing: Reducing Waste Before the Blade Leaves the Factory

Blade manufacturing itself generates a significant volume of composite waste, off-cuts, rejected laminates, and scrap from the trimming of cured blade surfaces. This manufacturing scrap is actually easier to manage than end-of-life blades because it is generated in a predictable, concentrated location and has not yet been exposed to 20 years of outdoor weathering.

Composite waste minimisation in production: Each MW of installed wind capacity requires roughly 9.57 to 13.41 tonnes of composite blade material. Approximately 25% of this, or 2.4 to 3.4 tonnes per MW, becomes waste over the turbine's lifecycle, arising from manufacturing scrap, service and maintenance, and end-of-life decommissioning[119].

Alternative and bio-based materials: Some manufacturers are experimenting with replacing balsa wood used as a core material in blades, which raises supply chain and sustainability concerns given sourcing from tropical forests with alternatives such as synthetic PET foam. LM Wind Power has minimised balsa in its blades, substituting synthetic plastic PET and PVC foams, and the share of blades using PET as core material instead of balsa has been growing rapidly[120]. Separately, bio-based resins derived from plant materials such as NREL's PECAN resin, which emits 40% less greenhouse gas during production than conventional epoxy are in development, though not yet at commercial scale.

C End-of-Life Integration: Keeping Blades Out of Landfills

Given that the majority of India's installed blade stock uses conventional thermoset composites the kind that cannot yet be closed-loop recycled at commercial scale, the immediate priority is developing practical, scalable end-of-life pathways for the blades that are already approaching decommissioning. Two routes are available now, and one is on the horizon.

Blade repurposing: The most immediate and cost-effective option for decommissioned blades is structural repurposing or finding applications where the blade's inherent properties such as high strength, light weight, weather resistance add value without requiring material separation. Internationally, this has included pedestrian bridges in the Netherlands and Poland; noise barriers along highways; structural elements in buildings; and playground equipment. For India, the most promising applications are likely in rural and peri-urban infrastructure small footbridges over irrigation canals, shade structures at bus stops and rural markets, and noise barriers along the national highway network, which is rapidly expanding.

India's scale of blade decommissioning in the near term beginning with the repowering of approximately 25 GW of sub-2 MW turbines creates a predictable and substantial supply of composite structures. **Matching this supply to demand in construction and infrastructure requires a national inventory of**

decommissioned blades, a standardised assessment process for structural integrity, and connections between wind developers and state public works departments. None of this currently exists, but the building blocks are available: the Ministry of New and Renewable Energy's repowering policy (December 2023), the upcoming PLI scheme for wind components, and India's massive infrastructure pipeline under the National Infrastructure Pipeline all create natural entry points for formalising blade repurposing pathways.

Cement co-processing: an industrial-scale near-term solution: Where repurposing is not possible, cement co-processing represents the most commercially viable current option for managing composite blade waste at scale. The process involves shredding blades and feeding them into cement kilns, where the organic content is combusted as a fuel substitute and the mineral fibres are incorporated into the cement clinker. One tonne of blade waste co-processed in cement kilns reduces cement CO_2 emissions by 110 kg and saves 461 kg of raw materials making it a genuine circular contribution to the cement industry, not merely waste disposal[121].

In the US, Vestas co-processed almost 300 blades from repowering projects through cement kilns in 2021, while GE Renewable Energy has established partnerships with LafargeHolcim and Veolia to shred fiberglass blades for cement manufacturing at commercial scale[122]. **India's cement majors like UltraTech, Ambuja, ACC, Dalmia already operate alternative fuel and raw material programmes at their kilns. Formalising a blade waste co-processing stream within these programmes, in partnership with wind developers and the MNRE, would provide an immediate and scalable disposal route for decommissioned blades from India's repowering programme.**

In the US, Vestas co-processed almost 300 blades from repowering projects through cement kilns in 2021, while GE Renewable Energy has established partnerships with LafargeHolcim and Veolia to shred fiberglass blades for cement manufacturing at commercial scale.

8.3 IMPACT IMPLICATIONS: WHY CIRCULARITY IN CLEANTECH MANUFACTURING IS A STRATEGIC IMPERATIVE FOR INDIA

The shift to circular manufacturing in India's cleantech sector generates impact across four interconnected dimensions: mineral security, industrial competitiveness, environmental integrity, and employment. None of these operate in isolation, and none are sector specific. They are systemic consequences of the same underlying reality: India has built one of the world's largest cleantech manufacturing bases but our import dependence makes this foundation exposed to global headwinds.

Reducing import dependence and strengthening mineral security

India currently spends approximately $2.5 billion annually importing critical minerals for batteries alone. In solar, the direct upstream import bill across silicon wafers, unassembled cells, and assembled modules

reached ₹31,572 crore ($3.6 billion) in FY26, with cells alone accounting for ₹22,021 crore at volumes 5.6 times higher than FY23. GTRI estimates that meeting India's 500 GW renewable target could push the total solar equipment import bill to $30 billion annually by 2030 if upstream manufacturing does not scale. The combined cleantech import exposure battery minerals plus solar upstream components already exceeds $6 billion annually and is structurally linked to a single dominant supplier

Circular interventions can address these vulnerabilities simultaneously. Recycling could address 30—40% of India's lithium demand by 2030. Silicon kerf recovery and silver recycling from solar manufacturing scrap and end-of-life modules can progressively substitute imported virgin materials. The IEA estimates that by 2040, recycled quantities of copper, lithium, nickel, and cobalt from clean energy applications globally could reduce primary supply requirements by 10—30% and hence for India, whose import exposure is sharper than most major economies, the domestic benefit would be proportionally greater. Crucially, mining projects average 18 years from discovery to first production. No overseas mineral asset acquisition, however, strategically sound, can deliver supply security within a decade. Domestic recycling of the batteries, panels, and turbines already deployed is the fastest and most controllable route to material security functioning as an urban mine within India's own borders and resilient to global shocks.

The sequencing of these opportunities matters: silicon kerf recovery at India's nascent but fast-scaling ingot and wafer manufacturing facilities represents the most immediate and structurally accessible circular intervention available today, requiring no reverse logistics and delivering direct input cost reduction at the point of manufacture, while battery recycling, though equally compelling in strategic terms depends on end-of-life volume accumulation, chemistry clarity, and reverse logistics infrastructure that will not converge until the early-to-mid 2030s.

Stabilising production costs and improving competitiveness

Global critical mineral markets are acutely volatile. Lithium spot prices fell 75% between 2022 and 2023; cobalt, nickel, and graphite dropped 30—45% over the same period. Indian manufacturers sourcing exclusively from primary markets absorb this volatility directly into their cost structures, compressing margins and complicating long-term investment planning. Domestically recycled material provides a price-stable, supply-secure alternative that no import contract can replicate.

Beyond input cost stabilisation, circular manufacturing is increasingly a condition of export market access rather than merely a cost-reduction strategy. European and North American markets are applying carbon border adjustment mechanisms and lifecycle emissions requirements to clean energy products. As the EU's Circular Economy Act introduces waste codes for decommissioned wind turbine blades and the Carbon Border Adjustment Mechanism matures, Indian manufacturers that cannot demonstrate end-of-life management pathways and low-lifecycle-emissions production will face market access barriers. Conversely, those that can demonstrate closed-loop or co-processing pathways gain a differentiated position in markets increasingly demanding sustainable supply chains.

Reducing the carbon footprint of manufacturing itself

India's cleantech manufacturing sector carries a significant embedded carbon burden : polysilicon production and wafer slicing are energy-intensive, and India's grid remains coal-heavy. A silicon recycling infrastructure based on kerf recovery combined with end-of-life module recycling could reduce the carbon emissions of PV-grade silicon production by up to 80% compared to conventional mining and refining. Life cycle assessments confirm that recycling end-of-life crystalline silicon panels rather than landfilling produces a substantially lower carbon footprint. For wind, the circular logic is even more direct: extending turbine life through refurbishment and repowering keeps embodied energy in existing structures, avoiding the full manufacturing emissions of new turbines. Wind turbines can function for up to 25 years — every year of life extension is a year of avoided manufacturing.

These gains are not merely environmental but are also commercial. As sustainability reporting requirements tighten and institutional investors increasingly apply lifecycle emissions criteria to cleantech supply chains, the carbon intensity of manufacturing inputs will directly affect access to capital and offtake contracts.

Building new industrial capacity and formalising employment

India's solar waste is concentrated in five states, all of which have established industrial and MSME ecosystems[123]. Battery waste is concentrated near urban EV adoption centres and existing manufacturing clusters. Wind blade decommissioning is concentrated in Tamil Nadu, Gujarat, and Maharashtra. This geographic concentration is not an obstacle, but it is an industrial development opportunity. Cluster-based recycling facilities co-located with manufacturing hubs eliminate reverse logistics costs, create stable feedstock pipelines, and generate employment across collection logistics, sorting, dismantling, delamination, precious metals refining, and secondary material trading.

NITI Aayog's recommendation for cluster-based Common Facility Centres for e-waste and lithium-ion battery recycling under the MSME Cluster Development Programme points toward a model that can formalise and upskill the approximately 500,000 workers currently employed in the informal recycling sector without safety infrastructure or formal certification. The circular economy, properly designed, does not merely manage waste but it creates an entirely new industrial value chain from what would otherwise be a liability, building the skilled workforce that India's cleantech ambitions will require at every stage of the material cycle.

The cost of inaction

The impacts described above are available only if India acts within a narrowing window. The decommissioning wave for first-generation wind turbines and early solar installations is arriving now, not in the 2030s. Without collection infrastructure, recycling capacity, and EPR frameworks in place before volumes peak, the default outcome is landfill, informal processing, and the environmental and reputational damage that follows. Europe's wind industry recognising that composite blades resist conventional recycling committed to a self-imposed sector-wide ban on landfilling decommissioned blades, effective January 2026, while calling on the EU to enshrine it in law[124]. India, which has positioned clean energy manufacturing as a national economic and environmental priority, cannot afford to let blade waste or solar panel graveyards become the defining image of its energy transition. Acting now, while volumes are still manageable, is dramatically cheaper and less politically difficult than addressing a well-established crisis later.

India's cleantech manufacturing landscape is broader and more ambitious than the three sectors examined in this report. The National Manufacturing Mission identifies solar cells, wind turbines, grid-scale batteries, electrolysers, and very high-voltage transmission equipment as priority cleantech manufacturing segments and India's green hydrogen ambitions targeting 5 million tonnes of annual production by 2030 under the National Green Hydrogen Mission are adding electrolysers and fuel cells to the frontier of domestic industrial capability. India's innovation agenda increasingly extends to hard-to-abate sectors through green hydrogen derivatives such as green ammonia and methanol, as well as advanced biofuels for decarbonising steel, fertilisers, refining, and shipping[125].

Yet solar PV, batteries, and wind energy are not merely three sectors among many, but they are the material foundation on which everything else rests. They are the sectors that have already reached gigawatt-scale manufacturing in India, that have existing and fast-accumulating end-of-life waste streams, and that have the most developed, if still nascent policy and regulatory architecture for circularity. Green hydrogen, electrolysers, and transmission equipment are critical frontiers, but their circular economy challenges are still largely prospective: the waste volumes are small, the manufacturing base is early-stage, and the end-of-life material flows are decades away. For solar, wind, and batteries, the decommissioning wave is not theoretical, but it is arriving now. Circularity in these three sectors is not a future aspiration, but it is an immediate industrial and strategic imperative, and the window for building the enabling infrastructure before waste volumes overwhelm policy is closing.



08



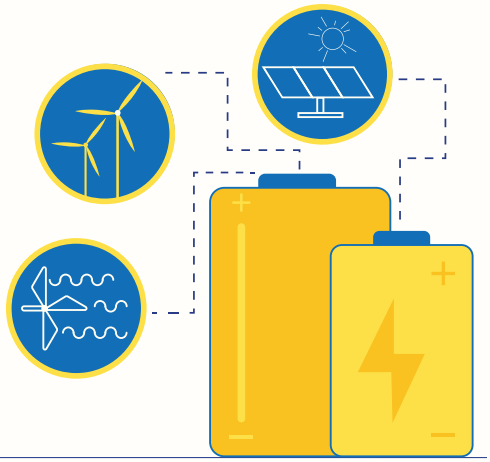
ENABLERS

Determinants of circularity in India's clean-tech manufacturing are no longer primarily technological.

Recovery processes capable of returning

90–95% OF HIGH-VALUE MATERIALS

to battery-grade or solar-grade purity have been demonstrated at industrial scale globally, and several are already being deployed by Indian firms.



What now separates a functioning circular industrial system from a stalled one is institutional: the structure of prices, taxes, logistics, standards, and enforcement within which recovery either becomes a competitive business or remains a compliance cost. Accordingly, this chapter treats enablers and barriers not as two separate lists. Most of India's enabling conditions are real but incomplete and almost every corresponding barrier is the unfinished half of the same instrument.

A regulatory architecture that precedes the waste wave. India's most distinctive enabling condition is timing. Unlike most economies, which constructed end-of-life regulation only after waste volumes became a visible crisis, India has put the principal regulatory architecture in place a decade or more before its clean-energy waste streams peak. The Battery Waste Management Rules (2022) established mandatory extended producer responsibility with phased collection targets and a centralised digital credit system; successive amendments through 2025 have[126] added compulsory digital labelling through barcodes, a public registry of obligated entities, an upward revision of the certificate floor price, and legally mandated environmental compensation charges for shortfalls. The E-Waste (Management) Rules (2022) brought solar PV modules and cells under a national framework making India one of the first jurisdictions outside the European Union to do so with a mandated producer storage obligation that effectively reserves the 2024—2035 period for infrastructure-building before end-of-life obligations bind. The National Repowering and Life Extension Policy (2023) provides at least a partial instrument for wind. The significance of this architecture is less its current enforcement quality, which remains uneven, than its existence: the legal categories, registries, and obligation structures that other countries had to improvise under crisis conditions are already in statute in India, and the policy task is consolidation rather than creation.

Fiscal policy that has begun to shift from deployment to circularity. A second enabling shift, visible only in the past two years, is the extension of India's industrial policy, previously concentrated on manufacturing capacity through the PLI schemes to material recovery itself. The Incentive Scheme for Promotion of

Critical Mineral Recycling, approved in September 2025 with an outlay of ₹1,500 crore under the National Critical Mineral Mission[127], provides a 20% capital subsidy on plant and machinery and an operating subsidy linked to incremental sales, with per-entity ceilings of ₹50 crore for large firms and ₹25 crore for smaller ones and one-third of the outlay earmarked for start-ups and new entrants. The scheme's design targets are material, with 270 kilotonnes of annual recycling capacity, roughly 40 kilotonnes of recovered critical minerals per year, ₹8,000 crore of mobilised private investment, and about 70,000 direct and indirect jobs over its six-year tenure[128]. Notably, the guidelines restrict incentives to the actual extraction of critical minerals excluding the production of black mass which is a deliberate attempt to pull Indian recycling up the value ladder from mechanical pre-processing toward hydrometallurgical refining, precisely the transition the sectoral analysis in this report identifies as decisive. This is complemented on the input side by the Union Budget 2025—26, which fully exempted basic customs duty on cobalt powder, lithium-ion battery waste and scrap, and more than a dozen other critical minerals, lowering feedstock costs for domestic recyclers during the period before domestic end-of-life volumes mature.

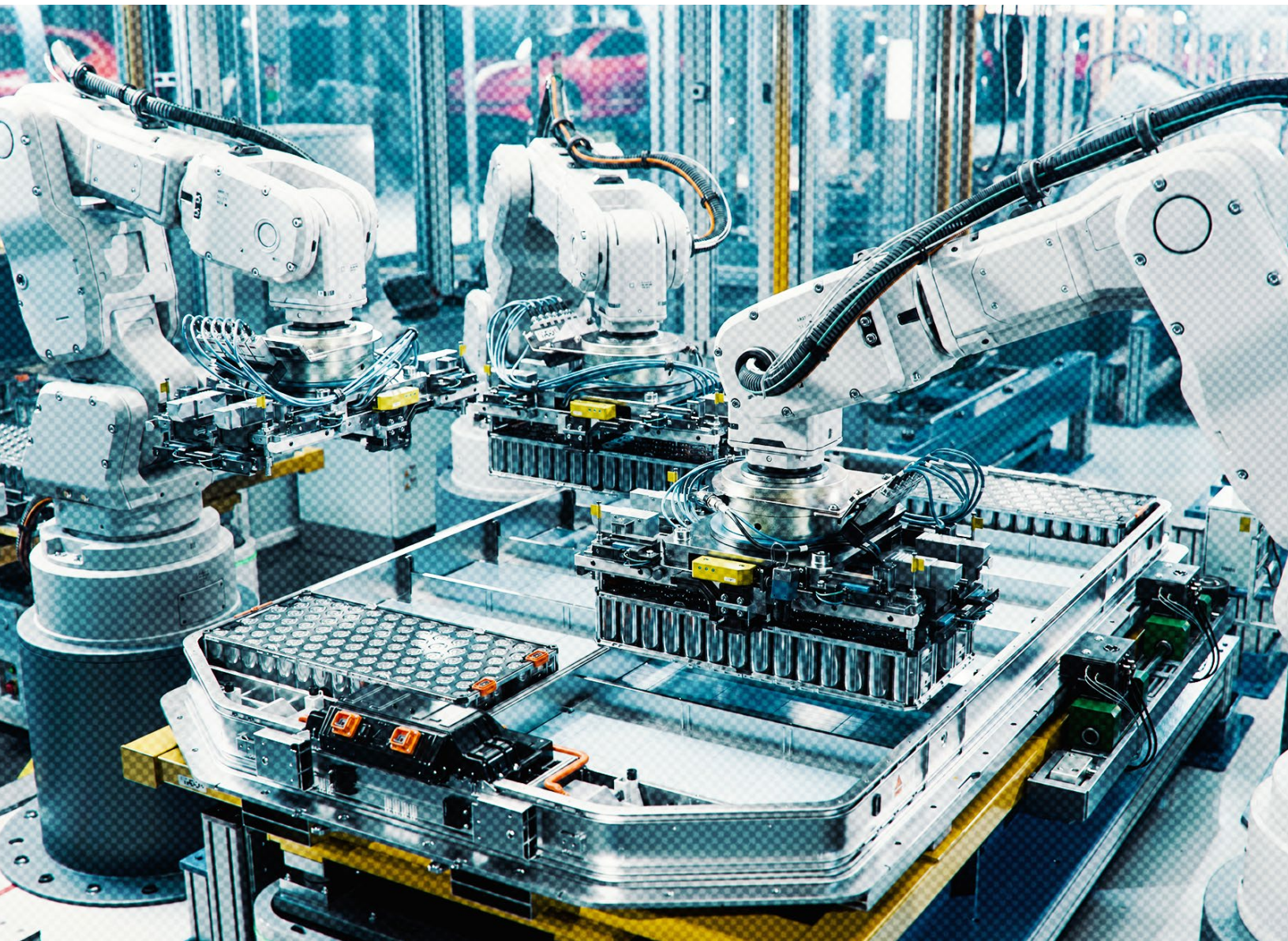
First, the BWMR amendments introduced minimum recycled-content obligations for battery producers, rising from 5% in n FY2027-28 toward 20% by FY2030-31which, if enforced, convert recovered material from a discretionary purchase into a regulatory requirement, mirroring the demand-creation logic of the EU Battery Regulation.

Assured demand: recycled-content mandates anchored to a fast-growing manufacturing base. Circular supply is only investable where circular demand is predictable. Two features of the Indian market now provide that anchor. First, the BWMR amendments introduced minimum recycled-content obligations for battery producers, rising from 5% in n FY2027-28 toward 20% by FY2030-31 which, if enforced, convert recovered material from a discretionary purchase into a regulatory requirement, mirroring the demand-creation logic of the EU Battery Regulation. Second, and more immediately, the sheer pace of India's manufacturing scale-up generates its own feedstock as this report's sectoral assessments show, manufacturing scrap which is homogeneous, uncontaminated, and concentrated at known factory locations which is essentially the dominant near-term recycling feedstock globally, and India's expanding cell, module, and blade plants will produce it in rising volumes years before end-of-life flows arrive. The co-location opportunity this creates, particularly in states like Gujarat's converging solar, wind, and battery manufacturing geography, allows circular capacity to be built against a bankable feedstock.

A private investment ecosystem that has moved past proof-of-concept. The financing environment for clean-tech circularity in India, while still thin, is slowly deepening. Domestic recyclers have raised some growth capital and the sector now attracts a layered capital stack spanning venture equity, NBFC and revenue-based debt, and growing interest from development finance institutions, which view the sector's nascence as precisely the stage at which concessional capital is catalytic[129]. Multilateral engagement is also materialising since GEF-supported, UNDP-implemented programme approved in 2025 combines USD 15 million in grant financing with over USD 105 million in government and industry co-financing

to strengthen e-waste enforcement, eco-design, and recovery infrastructure[130]. India's battery recycling market is projected to grow at roughly 18% annually through 2034[131], well above the global average and this is a growth premium that reflects both the scale of the underlying waste flows and the policy support now attached to them.

Industrial geography, institutional assets, and an existing workforce. Finally, India enters the circular transition with endowments that most emerging economies lack. Its clean-tech waste streams are geographically concentrated with over two-thirds of projected solar waste in five states, wind capacity in seven, battery flows clustered around EV-adopting urban centres which converts the reverse-logistics problem from a national-scale challenge into a sequence of regional ones. The country's 200-plus large cement kilns with established alternative fuel and raw material programmes constitute a latent, near-term disposal and co-processing network for composite blade waste that Europe had to assemble from scratch. Its engineering talent pipeline of over a million graduates annually, IIT and CSIR research capacity in recycling chemistry, and three decades of wind O&M workforce experience provide the human-capital base for an industry that does not yet formally exist. Additionally, the informal sector's half-million workers represent an unmatched collection and dismantling network whose reach if formalised rather than displaced is itself an enabler no greenfield formal system could replicate quickly.



09



BARRIERS AND FRICTIONS

The economics gap: a floor price that does not cover the floor. The single most consequential barrier to formal battery circularity in India is that the price signal at the heart of the EPR system is set below the cost of compliant recycling. The EPR certificate floor price under consideration for lithium-ion batteries appears strikingly low and well below the levels set by advanced economies with comparable schemes, even after accounting for differences in purchasing power, while the true cost of safe dismantling, hazardous-material handling, and high-recovery processing remains substantial. This gap risks leaving formal recyclers unable to operate sustainably. The 2025 BWMR amendments revised the floor upward, but the structural problem persists wherever certificate prices track the lowest-cost and lowest-integrity supplier. The economics gap is further compounded by the dominance of LFP chemistry in India's gigafactory pipeline, whose low residual metal value makes recycling uneconomic without mandate and the extreme volatility of critical mineral prices with lithium falling more than 80% from its 2022 peak. This makes recovered-material revenues impossible to project with the confidence that project finance requires. To attract investment for high value recycling, there should be instruments to stabilise the value of recovered material, ensure assured offtake and stricter enforcement for recycled content.

Fiscal distortions that tax circularity and subsidise informality. India's tax system currently makes it more expensive to recycle formally than informally. A recycler pays 18% GST when buying scrap, e-waste, or end-of-life batteries, but charges only 5% on many of the recycled products it sells. The difference cannot be easily recovered, so it sits locked up as unrefunded tax credit which a constant drain on working capital that hits hardest the small and medium enterprises that make up most of the sector[132]. Informal traders on the other hand face buy and sell in cash, outside the tax net altogether. The practical effect is that the 18% rate operates as a penalty on being formal. This means that the compliant recycler starts every transaction at a cost disadvantage to the informal one. Some correction has begun in 2024, the GST Council shifted responsibility for paying tax on scrap purchases to the registered buyer and added a 2% deduction at source, creating a paper trail at exactly the point where informal supply enters the formal chain[133]. But the basic rate gap remains untouched, and industry continues to press most recently ahead of Budget 2026 for lower GST on recycled and low-carbon materials[134]. The principle at stake is simple: a tax system that makes recovered material more expensive to use than virgin material cannot coexist with a national circularity objective.

The reverse-logistics vacuum. Between dispersed waste and centralised recovery lies a physical and regulatory gap that no incentive scheme currently addresses. Lithium-ion batteries are classified as dangerous goods, yet India lacks a fit-for-purpose national framework for their handling, storage, and transport and this is a gap the Battery Waste Management Rules themselves identify as a binding constraint. The formal collection network is thin to the point of nominal coverage: roughly 2,800 authorised collection centres serve a population of 1.4 billion, while formal channels capture under 5% of end-of-life batteries and around 10% of e-waste[135]. The problem differs by technology but is unresolved

in all three sectors examined in this report: batteries dispersed across consumer and fleet locations with no compliant transport pathway, solar modules that are large, fragile, and scattered across utility parks and rooftops with no aggregation infrastructure and wind blades approaching 100 metres that cannot be moved whole on most Indian roads and must be cut on site, at unplanned cost, with no designated destination. This created an asymmetry wherein formal recyclers bear higher cost of regulated movement.

The informal sector and the formalisation dilemma. The informal economy is simultaneously India's largest existing circular asset and its most difficult policy problem. Informal operators handle an estimated 90% of end-of-life batteries and around 62% of e-waste[136], employing roughly half a million workers whose collection reach no formal network matches, but whose acid-leaching and open-burning recovery methods impose severe health and environmental costs and lose much of the material value that scientific processing would capture. The design question the current framework has not answered is whether formalisation will integrate this workforce through aggregator registration, technical upgradation, occupational health protection, and cluster-based common facilities or simply license a parallel formal sector that competes with and criminalises it. International experience and India's own plastic-EPR record suggest that displacement-style formalisation fails twice over. It forfeits the informal sector's collection efficiency while pushing hazardous processing further from regulatory view. No formal qualification framework yet exists for circular-economy occupations, recycling operations, second-life battery assessment, composite waste handling leaving the skilling system without the categories it would need to absorb this workforce.

Feedstock timing, technology gaps, and the missing midstream. A subtler barrier is temporal: circular capacity and circular feedstock are scaling on different clocks. Globally, announced recycling capacity is running ahead of available end-of-life material in China, plants would average only around 20% utilisation even if all available material were processed and India risks importing this "valley of death" in reverse sequence. Its recyclers face thin feedstock now, against capacity that is being subsidised ahead of it: the recycling incentive scheme alone targets 270 kilotonnes of annual capacity by 2031, a figure of the same order as the entire volume of end-of-life lithium-ion batteries projected to be available in 2035. Bridging the lean years requires the feedstock the incentive scheme's design acknowledges, manufacturing scrap and imported scrap and yet much of India's recovered black mass is still exported for refining abroad because the domestic midstream that would absorb it like cathode-precursor and active-material production barely exists. The technology frontier compounds the gap, and India has no commercial-scale direct recycling, no demonstrated high-value pathway for thermoset blade composites, and limited domestic capability in the hydrometallurgical selectivity on which battery-grade output depends. Until recovered materials can be sold into domestic manufacturing at battery and solar grade, Indian circularity will remain an extraction business serving other countries' closed loops.

Measurement, standards, and enforcement deficits. Finally, the system lacks the verification infrastructure on which every other instrument depends. Recycled-content verification faces a similar gap in the absence of BIS-anchored standards, the 5—20% mandates cannot be independently audited, and the EPR certificate regime continues to grapple with its central challenge of reliably verifying that certified recycling has actually taken place[137].The 2025 amendments' mandatory barcoding and public registry move in the right direction, and the EU's battery passport provides a tested template whose adoption

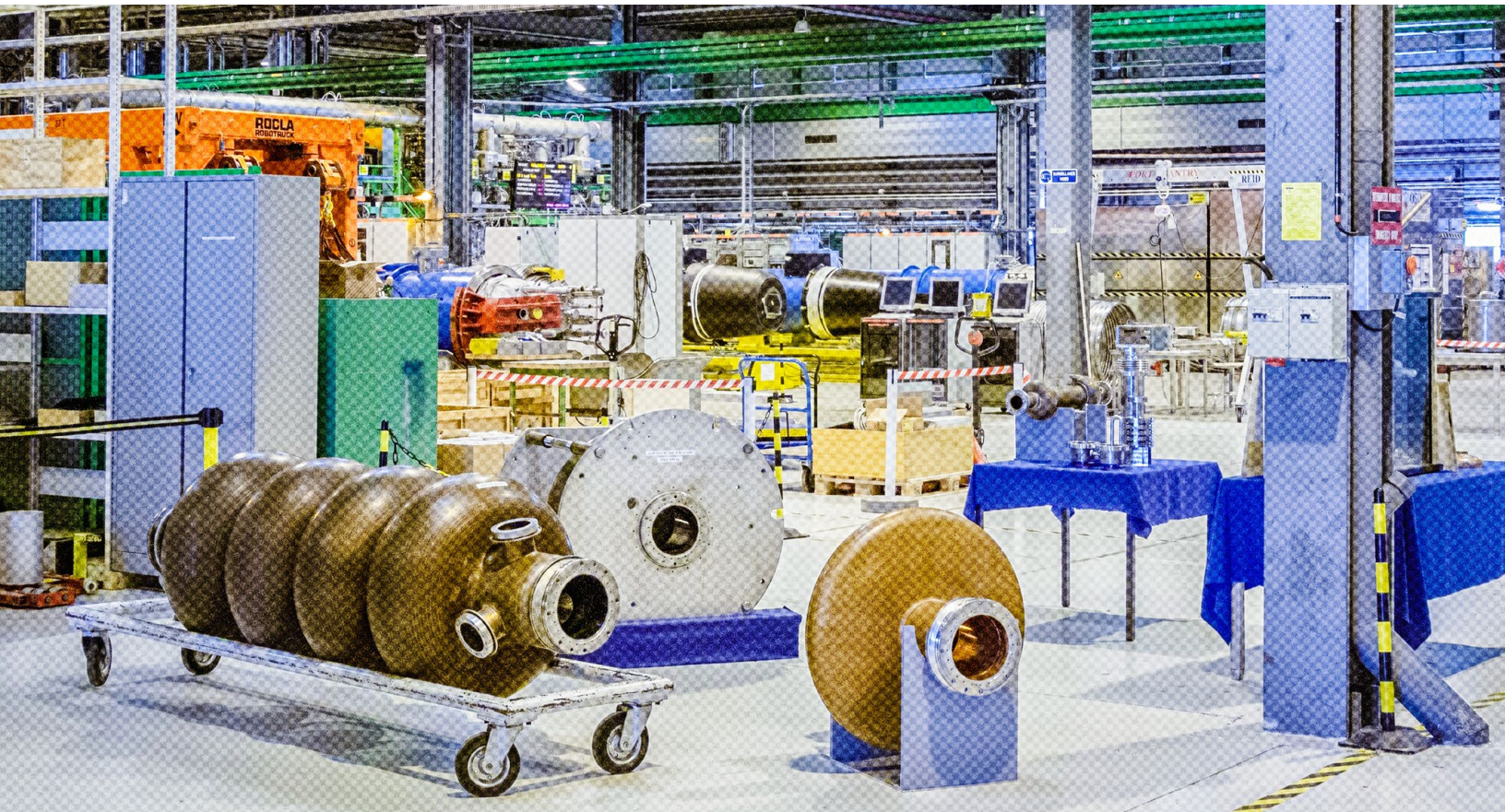
would serve domestic traceability and export-market access simultaneously. But until the measurement layer exists, enforcement is conducted on paper claims, and every price signal in the system from the floor prices, credits and recycled-content premiums can be gamed.

Synthesis: Where the Binding Constraints Lie

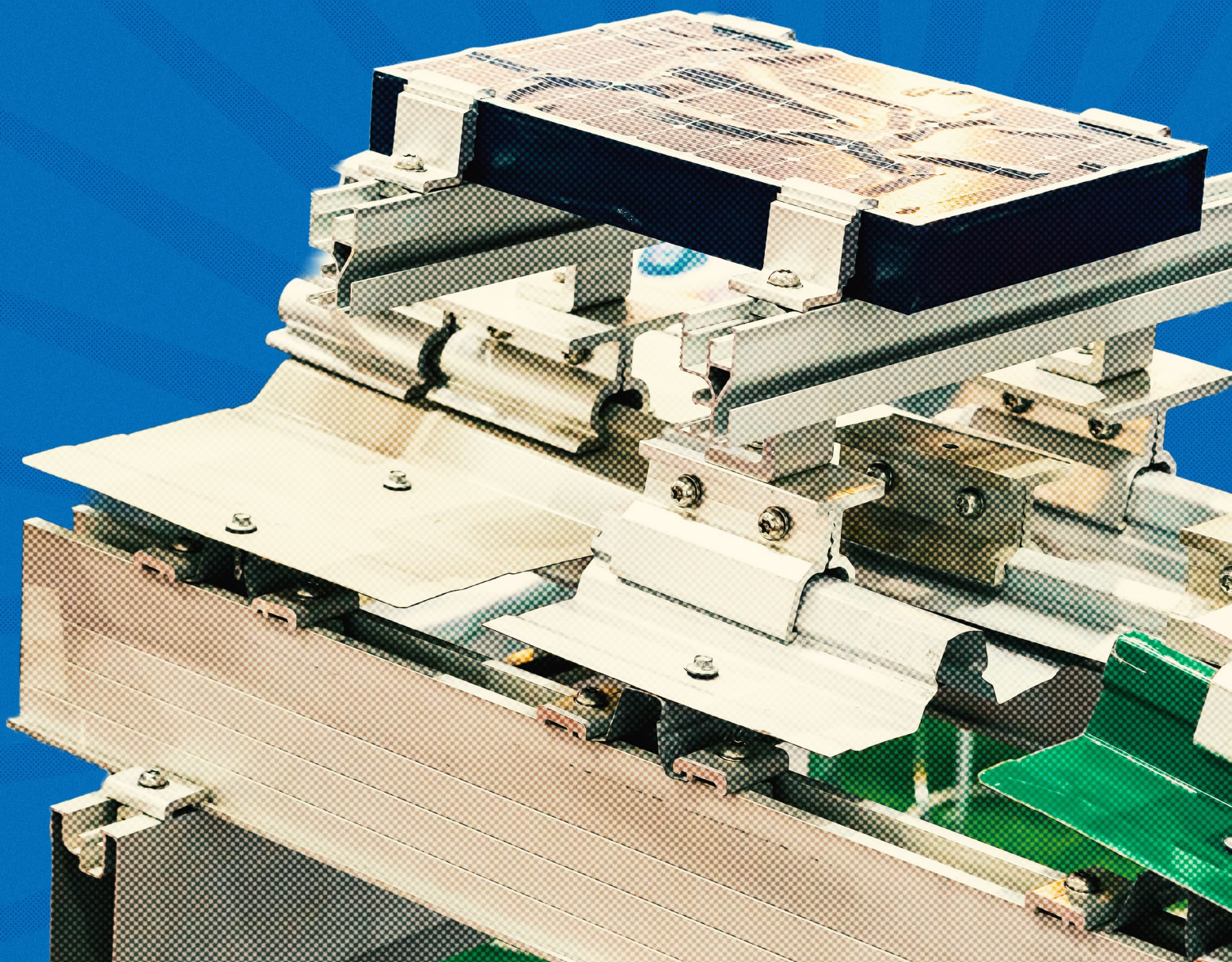
Viewed together, India's enablers and barriers reveal a structural asymmetry. The enabling conditions are concentrated on the supply side of circularity, in the form of subsidised capacity, duty-exempted feedstock, a regulatory architecture already in statute, and waste streams clustered in a handful of states. The barriers are concentrated where markets are actually made: in demand, price formation, and trust. A floor price set below the cost of compliant recycling, a tax structure that penalises formality, a logistics regime under which the material cannot legally move, and a verification layer too weak to make any market instrument credible together determine whether subsidised plants ever receive feedstock or earn revenue.

This asymmetry carries a direct implication for sequencing. Additional capital subsidy will yield diminishing returns so long as the conditions governing revenue remain unreformed, because capacity without viable economics is simply stranded investment. The highest-leverage interventions are therefore those that repair price and trust together. These include a cost-reflective and periodically indexed EPR floor price backed by audited issuance, GST rationalisation that removes the penalty on formal operation, a notified hazardous-transport framework for lithium-ion waste, recycled-content enforcement tied to PLI eligibility, and a phased national traceability system aligned with emerging international product passports.

What distinguishes this reform agenda is its modesty in everything except discipline. None of these measures requires new technology, and most demand no outlay comparable to the incentives already committed. They require instead the completion of instruments India has already half-built.



10



FROM AMBITION TO ARCHITECTURE

India's cleantech circularity transition is, on the evidence assembled in this report, not an environmental refinement layered onto industrial strategy, but a strategy on its own. India has built one of the world's largest clean-energy manufacturing bases on an import-dependent, linear foundation: over USD 6 billion a year flows out for minerals and components sourced overwhelmingly from a single dominant supplier, even as the panels, batteries, and blades already deployed move steadily toward end-of-life with no infrastructure in place to recover them. The waste wave now building across all three sectors contains the very materials India imports at near-total dependence, which makes it less a disposal problem than a domestic reserve waiting to be claimed. The distance between what India buys and what India discards is the space in which circular policy must now operate.

The diagnosis is consistent across all three value chains. India has built ambition and supply: production incentives at scale, an EPR framework with escalating recovery and recycled-content obligations, solar PV brought under regulation a decade before its waste wave, a critical mineral mission with recycling written into its mandate, and a manufacturing base expanding faster than almost anywhere in the world. What it has not yet built is the connective tissue where markets are actually made, a price signal that covers the cost of compliant recycling, a tax structure that does not penalise formality, a legal pathway for hazardous material to move, collection infrastructure with real reach, standards against which recycled content can be verified, and a domestic midstream capable of absorbing what is recovered. The enablers and barriers examined above are two readings of the same underlying fact that almost every barrier is the unfinished half of an instrument that already exists.

What must move in the next five years

- Make recycled-material sourcing a condition of PLI eligibility for battery and solar manufacturers, creating the assured domestic demand for recycled content without which the recycling investment case cannot close.

- Introduce product design requirements like recycled-content thresholds, design-for-disassembly standards, and traceability as market-entry conditions for batteries and solar modules, following the EU Battery Regulation 2023 model, before the first wave of large-scale end-of-life arrives after 2035.

- Establish a fit-for-purpose hazardous-material transport framework for spent lithium-ion batteries, resolving the regulatory gap that currently advantages informal operators over formal recyclers and suppresses investment in formal collection infrastructure.

- Scale PRISM and analogous programmes for circular cleantech innovation, with a particular focus on composite material separation for wind turbine blades, a stream that must have processing capacity in place before annual blade waste roughly quadruples to its 96,050-tonne peak in 2036—37.

Among the major economies, India has put its regulatory architecture in place a decade before its clean-energy waste streams peak: the legal categories, registries, and obligation structures that other countries improvised under crisis conditions are already in statute. India retains what most industrial powers have forfeited, which is a design-stage window. Its first gigafactories, cell lines, and wafer plants are being specified now, and the choices made in this window will determine, for decades, whether India's clean-energy hardware is built to be recovered or built to be discarded. The barriers are real, but they are, without exception, problems of completion rather than creation, and that is precisely why they can be solved. The transition from a manufacturing base that imports and discards to one that recovers and recirculates will not be won through new schemes layered on top of old ones, but through the patient work of finishing the instruments India has already half-built before the wind decommissioning spike of 2035—37 arrives, before the solar producers' storage obligation runs out in 2034—35, and while the design window is still open. Ambition has carried India's cleantech manufacturing this far but architecture must carry it the rest of the way.

APPENDIX

01 ESTIMATION OF INDIA'S SOLAR IMPORT DEPENDENCY

Methodological Note

Objective

This appendix describes the methodology used to estimate India's direct import dependency in solar photovoltaic supply chains. It covers the value, volume, and source concentration of imports across three upstream product categories from FY2022—23 to FY2025—26.

Data Source

All import data was extracted from the DGFT (Directorate General of Foreign Trade) trade database, which provides commodity-level import statistics by country of origin in both value (₹ crore) and quantity terms on an annual basis.

Data item	Source	Notes
Import value by HS code and country (FY23—FY26)	DGFT Trade Statistics Database	In ₹ crore, nominal
Import quantity by HS code and country (FY23—FY26)	DGFT Trade Statistics Database	In NOS (cells, modules) and NOS (wafers)
Country-of-origin breakdown	DGFT Trade Statistics Database	Declared origin at customs

HS Codes Covered

Three HS codes were selected to capture India's direct solar supply chain imports. Together, they constitute what is referred to as the direct solar import bill in this report.

HS Code	Description
85414200	Photovoltaic cells, not assembled into modules or panels (solar cells)
85414300	Photovoltaic cells assembled in modules or made up into panels (solar modules)
38180010	Undiffused silicon wafers

Steps

- **Extract raw data**

  For each HS code, annual import data was extracted from DGFT for FY23—FY26, capturing total import value (₹ crore), import quantity (NOS for cells and modules; NOS for wafers), and country-of-origin breakdown for both value and quantity.

- **Compile total direct import bill**
  The three HS codes were summed by year to produce the aggregate direct solar import bill.

- **Calculate source country shares**
  For each HS code and year, each source country's share of total imports was computed in both value and quantity terms, expressed as a percentage of the world total reported in DGFT.

- **Derive unit prices**
  For cells (85414200) and modules (85414300), unit prices were derived by dividing total import value (converted to ₹) by total import quantity for each year. This allows trend analysis of price movements independent of volume changes.

- **China vs. non-China split**
  For each year, imports were disaggregated into China-origin and non-China-origin totals using the country-of-origin field directly from DGFT data.

Assumptions and Limitations

Scope

- Covers direct imports only across the three HS codes; indirect import dependency embedded in domestically assembled products is not captured
- Analysis period is FY2022—23 to FY2025—26

Limitations

- No seasonal adjustment or deflation has been applied; all values are in nominal ₹ crore
- World totals used for share calculations are as reported in DGFT and may include minor residual entries not disaggregated by named country

Reference

DGFT Trade Statistics Database, accessed 2026. Available at: https://www.dgft.gov.in

02 ESTIMATION OF WIND BLADE MATERIAL WASTE IN INDIA (UP TO 2040)

Methodological Note

Objective

This appendix describes the methodology used to estimate the volume of wind turbine blade material waste that India is likely to generate up to 2040, and how this waste is distributed across states. The exercise is designed to provide a factual basis for assessing the scale of the circular economy opportunity in India's wind sector.

Methodological Approach

The methodology draws primarily on Liu & Barlow (2017) and Heng et al. (2021). The central principle is that wind blade material waste is a function of installed turbine capacity. The approach involves three sequential steps:

- **Compile current installed capacity**
  State-wise and national cumulative installed wind capacity data from 2014—26 are sourced from the Ministry of New and Renewable Energy's Renewable Energy Statistics 2024—25 and a PIB release dated 2026.

- **Project future capacity additions**
  India's 2025 installed capacity of 56 GW is projected to reach 100 GW by 2030, consistent with the GWEC India Wind Report 2025 assessment. This implies average annual additions of 8.78 GW. The same annual addition rate is held constant from 2030 to 2040, representing a conservative mid-path assumption.

- **Calculate blade material and waste**
  Each year's capacity addition is converted to blade material using a fixed material intensity of 13.41 tonnes per MW, corresponding to turbines in the 2—5 MW class (Liu & Barlow, 2017). Waste is then estimated as a proportion of total blade material at three lifecycle stages (see Table 2 below). The central scenario from Liu & Barlow is applied throughout.

Data Source

Data item	Source	Notes
Historical installed wind capacity (2014—2026)	Renewable Energy Statistics 2024-25; PIB (2026)	State-wise cumulative GW figures
National capacity target (2030)	GWEC India Wind Report 2025; PIB (2025)	100 GW adopted as working target
Blade mass per MW by turbine class	Liu & Barlow (2017)	13.41 t/MW used (2—5 MW class)
Lifecycle waste rates (manufacturing, service, decommissioning)	Liu & Barlow (2017)	Central scenario applied
State-level capacity shares	Derived from historical installed base	Used for sub-national disaggregation

Key Parameters and Assumptions

Capacity trajectory

- Base year (2025—26): 56 GW installed capacity
- Target year (2030—31): 100 GW
- Annual addition: 8.78 GW (held constant through 2040)
- Post-2030 trajectory: same 8.78 GW/year (no policy guidance assumed; mid-path)

Blade material intensity

- Average turbine capacity assumed: slightly above 2 MW
- Blade mass applied: 13.41 tonnes per MW (2—5 MW class, Liu & Barlow 2017)
- This parameter is held constant over the projection period

Lifecycle waste rates (central scenario)

Year in lifecycle	Waste category	% of total blade material mass
Year 1	Manufacturing waste	17.2%
Year 6	In-service / maintenance waste	1.1%
Year 21	Decommissioning waste	100%

Total lifecycle waste sums to approximately 25% of blade material weight (excluding decommissioning). At decommissioning (year 21), 100% of blade material is treated as waste.

State-level disaggregation

Future capacity additions are distributed across states in proportion to each state's current share of national installed capacity. For example, Gujarat (approx. 27.9% of the national base) is allocated 27.9% of each year's national addition. Waste is then calculated at state level using the same lifecycle rates.

Scope and Limitations

Scope

- Covers waste from wind capacity additions from 2014—15 onwards only; pre-2014 installations are excluded
- Estimates blade material waste only; does not cover tower, nacelle, foundation, or cabling components
- Does not assess disposal pathways, lifecycle environmental impacts, or carbon footprints

Limitations

- Capacity projections are illustrative and sensitive to policy changes; the 100 GW by 2030 target may not be met
- Material intensity (13.41 t/MW) is drawn from international data and may not precisely reflect the turbine mix deployed in India
- Average turbine capacity is assumed constant at slightly above 2 MW; actual average capacity is likely to rise over the projection period, which would alter waste estimates
- State-level shares are held constant, whereas actual allocation of future projects may shift over time
- Lifecycle waste rates follow the central scenario from Liu & Barlow (2017); high- and low-end scenarios are not modelled here
- Decommissioning waste is determined by the assumed 21-year service life; actual decommissioning timelines will vary

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