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Silver as a Strategic Input in India's Renewable Energy Transition: Import Dependence, Price Volatility, and Policy Imperatives

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ABSTRACT

India's ambitious renewable energy expansion, particularly in solar photovoltaic (PV) capacity, has created substantial demand for critical materials, with silver emerging as a strategic input due to its indispensable role in PV cell manufacturing. This study examines the evolving relationship between India's solar energy deployment and silver demand dynamics during 2015-2025, analysing import dependency patterns, price volatility trends, and supply security challenges. Using descriptive analytics and trend analysis of secondary data from the Multi Commodity Exchange (MCX), World Silver Survey, Ministry of New and Renewable Energy (MNRE), and trade statistics, we demonstrate that India's heavy reliance on imported silver (exceeding 90% of consumption) creates significant vulnerabilities for renewable energy cost competitiveness and deployment timelines. Our findings reveal that industrial silver demand, driven primarily by solar PV manufacturing, has grown from approximately 15% to 33% of total Indian silver consumption between 2015 and 2025, while prices exhibited 67% volatility during the same period. The study contributes to resource security discourse in energy transitions by proposing an integrated policy framework encompassing circular economy approaches, strategic reserves, R&D investment in material efficiency, and supply chain diversification. We argue that treating silver as a strategic material rather than merely a traded commodity is essential for sustaining India's green energy trajectory and achieving its 500 GW renewable energy target by 2030.

Keywords: Silver demand, Solar photovoltaics, Renewable energy transition, Critical materials, Green economy

1. Introduction

India's pursuit of a green economy has gained unprecedented momentum over the last decade, driven by the twin imperatives of energy security and climate change mitigation. With rising energy demand projected to increase by 3-4% annually through 2030 (International Energy Agency, 2024), increasing import dependence on fossil fuels exceeding $120 billion annually, and growing international commitments toward decarbonization under the Paris Agreement, renewable energy has emerged as a central pillar of India's long-term development strategy. The country has set ambitious targets for renewable capacity expansion, aiming for 500 GW of renewable energy capacity by 2030, with solar energy contributing approximately 280 GW (MNRE, 2024). This positions India as one of the fastest-growing clean energy markets globally, with solar capacity additions averaging 10-15 GW annually since 2020.

While policy discussions and academic research have largely focused on capacity addition, financing mechanisms, grid integration challenges, and institutional frameworks, comparatively less attention has been paid to the material foundations that underpin the renewable energy transition. This represents a critical gap in understanding the full spectrum of constraints and enablers that may affect India's green energy ambitions.

Renewable energy technologies, despite being environmentally cleaner in operation, are highly material-intensive. Solar photovoltaic (PV) systems, in particular, rely on a range of critical minerals and metals to ensure efficiency, durability, and performance. Among these inputs, silver occupies a unique and strategic position. Owing to its superior electrical conductivity (63×10^6 S/m, the highest of all metals), minimal contact resistance, excellent resistance to corrosion, and thermal stability, silver is an indispensable component in high-efficiency solar cells, particularly in the metallization paste used for front and rear contacts in crystalline silicon PV cells (Ballif et al., 2022).

Unlike several other industrial metals, silver has limited scope for substitution without compromising technological performance, especially in advanced PV applications. While copper-based alternatives exist, they suffer from migration issues, lower conductivity, and reduced cell efficiency. Current PV technology utilizes approximately 12-20 mg of silver per watt of solar capacity, though this has decreased from earlier levels of 30-40 mg/W due to technological improvements in screen printing and paste formulation (ITRPV, 2024). As India's solar capacity continues to expand rapidly, the demand for silver from the renewable energy sector is expected to rise correspondingly, with projections suggesting annual requirements of 2,500-3,500 tonnes by 2030 for India alone.

Despite its significance, the strategic dimension of silver in India's renewable energy transition remains underexplored in academic and policy discourse. Most energy-focused studies emphasize technology costs, grid integration, and emission outcomes, while mineral and resource studies often treat silver independently of energy transition goals. This disconnect creates a critical gap in understanding how material inputs interact with energy policy and sustainable development objectives. Addressing this gap is crucial, particularly for a developing economy like India, where resource constraints and development priorities must be carefully balanced.

1.2 Research Objectives

1. To analyze trends in silver prices and demand in India over the period 2015-2025, identifying structural shifts related to renewable energy growth
2. To assess the extent of India's import dependence for silver and its implications for energy security
3. To estimate silver requirements for India's projected solar energy expansion through 2030
4. To identify strategic challenges related to silver supply security in the context of renewable energy deployment
5. To propose policy measures for enhancing material security and resilience in India's green energy transition

2. Literature Review

2.1 Silver in the Global Energy Transition

The transition to renewable energy systems globally has significantly altered the demand profile for various industrial metals, with silver emerging as a material of strategic importance due to its critical role in photovoltaic (PV) technologies. Traditionally, silver has been studied within the contexts of financial markets and monetary economics, with research focusing on price volatility, hedging behavior, inflation correlation, and portfolio diversification (Baur & Lucey, 2010; Sensoy, 2013). However, recent research highlights a growing industrial dimension tied to the energy transition, particularly through solar energy deployment.

One of the foremost trends identified in the literature is the structural increase in silver demand driven by the rapid expansion of solar PV capacity. Industry reports indicate that industrial demand for silver, especially from the PV sector, has been surging and constitutes a meaningful share of total consumption. For example, global industrial demand for silver has been underpinned by an increase in photovoltaic applications, and the silver market has been in a persistent physical deficit since 2021, demonstrating the structural nature of this demand shift toward green energy technologies (Silver Institute, 2024; pv-magazine International, 2024).

2.2 Quantitative Projections of Silver Demand from Solar PV

The quantitative importance of silver for PV manufacturing is addressed in recent academic work forecasting future materials requirements. Cattaneo et al. (2026) project that the photovoltaic industry will become one of the fastest-growing sources of silver demand, with annual requirements potentially reaching between 10,000 and 14,000 tonnes globally by 2030, accounting for 29-41% of global silver supply under certain deployment and technological scenarios. This represents a dramatic increase from approximately 3,000 tonnes consumed in 2020.

These projections signal both opportunities and supply-side challenges. Despite ongoing technological efforts to reduce silver loading per PV module, such as through "thrifting" (reducing paste thickness), alternative metallisation approaches (copper plating, screen printing innovations), and multi-busbar designs, the sheer scale of solar capacity growth continues to create upward pressure on overall silver demand (ITRPV, 2024). This is particularly important for emerging economies like India, which rely heavily on imports to meet raw material needs for renewable energy infrastructure, potentially exposing energy policy to global commodity market risks.

2.3 Recycling and Circular Economy Perspectives

Another important dimension in the literature is the lifecycle perspective, especially regarding recycling and material recovery. With the exponential growth of PV installations, end-of-life (EoL) waste streams will become substantial by 2035-2040, raising questions about resource circularity and sustainable material management. Rout et al. (2025) and Jadhav et al. (2024) provide comprehensive reviews of recycling technologies, underscoring the technical and economic potential of recovering silver from decommissioned PV panels. Current silver recovery rates from PV panels range from 85-95% in laboratory settings, though commercial-scale operations achieve lower rates of 60-75%.

However, challenges remain related to extraction efficiency, environmental impacts from chemical processes, economic viability at current silver prices, and the scalability of recycling systems. The long lifespan of solar panels (25-30 years) means that significant recycling volumes will only materialize in the 2040s, creating a temporal mismatch with current demand growth.

2.4 Material Security in Energy Transitions

Broader literature on critical materials in energy transitions provides relevant frameworks for understanding silver's strategic role. Sovacool et al. (2020) examine supply risks for various materials used in clean energy technologies, highlighting geopolitical concentration, price volatility, and demand surges as key vulnerability factors. Similar analytical approaches have been applied to lithium, cobalt, rare earth elements, and other materials, but silver has received comparatively less attention despite its criticality for solar PV.

The concept of "material criticality" typically involves two dimensions: supply risk and economic importance (European Commission, 2020). Silver exhibits moderate to high scores on both dimensions for countries heavily dependent on solar energy deployment, suggesting it warrants strategic policy attention comparable to other critical materials.

2.5 India-Specific Context

Research specifically examining India's material requirements for renewable energy remains limited. Existing studies on India's solar sector primarily focus on policy mechanisms (Renewable Purchase Obligations, competitive bidding), financial aspects (capital costs, levelized cost of energy), technical challenges (grid integration, intermittency), and socioeconomic impacts (employment generation, energy access).

Few studies have explicitly examined material supply chains for India's renewable energy sector. Khan and Bhattacharya (2023) provide an overview of critical mineral requirements for India's energy transition but treat silver peripherally. Similarly, NITI Aayog reports on critical minerals focus primarily on lithium, cobalt, and rare earths, with limited attention to silver despite its quantitative importance.

2.6 Research Gap

Research on India's renewable energy transition has primarily emphasized capacity expansion, financing, and emissions outcomes, while studies on silver have largely focused on its financial and price dynamics. As a result, silver's role as a critical material input for solar photovoltaic technologies remains underexamined, particularly in the Indian context. Existing material security literature concentrates mainly on battery minerals such as lithium and cobalt, implicitly overlooking the technological irreplaceability of silver in mainstream PV systems. Moreover, India-specific vulnerabilities high import dependence, exposure to global price volatility, and limited recycling capacity have not been systematically linked to renewable energy planning or green economy objectives. This study addresses this gap by providing an integrated, India-centric assessment of silver as a strategic input to the renewable energy transition, connecting material supply risks with energy policy and sustainability goals.

3. Methodology

3.1 Research Design

This study employs a descriptive analytical approach based entirely on secondary data. No econometric or statistical models are used, as the primary objective is to examine trends, patterns, and strategic implications rather than establishing causal relationships or predictive models. This methodological choice is justified by the exploratory nature of the research question and the need to establish foundational understanding before advancing to more sophisticated analytical techniques.

The study period spans 2015-2025, chosen to capture the recent acceleration in India's solar energy deployment and corresponding shifts in silver demand dynamics. This ten-year window provides sufficient temporal variation to identify meaningful trends while maintaining data consistency and comparability.

3.2 Data Sources

- **Silver Prices**: Multi Commodity Exchange (MCX) monthly silver futures prices
- **Silver Demand/Supply**: World Silver Survey published by the Silver Institute
- **Renewable Energy**: Ministry of New and Renewable Energy (MNRE) and International Renewable Energy Agency (IRENA)
- **Trade Statistics**: Reserve Bank of India (RBI) and Directorate General of Commercial Intelligence and Statistics (DGCIS)
- **Technical Parameters**: International Technology Roadmap for Photovoltaic (ITRPV)

3.3 Analytical Approach

The analysis is conducted through several complementary techniques:

1. **Trend Analysis**: Time series data are plotted and examined to identify patterns, structural breaks, and directional changes in silver prices, demand composition, and import dependence.
2. **Comparative Analysis**: India's position is benchmarked against global trends and other major silver-consuming economies where relevant.
3. **Projection Calculations**: Silver requirements for future solar capacity are estimated using current technical parameters for silver intensity (mg per watt) applied to official renewable energy targets, with sensitivity analysis for different technological scenarios.
4. **Qualitative Assessment**: Policy documents, industry reports, and expert commentary are synthesized to contextualize quantitative findings and derive strategic implications.

4. Analysis And Interpretation

4.1 Silver Price Volatility in India

Silver prices in India have exhibited considerable volatility over the past decade, reflecting both global commodity market movements and domestic macroeconomic conditions. Figure 1 presents the monthly average silver prices on the Multi Commodity Exchange (MCX) from January 2015 to December 2025, demonstrating a long-term upward trend punctuated by sharp fluctuations during periods of global financial uncertainty, currency depreciation, and heightened industrial demand.

Notably, price surges after 2020 coincided with strong global demand for green technologies, particularly solar photovoltaics, alongside supply-side constraints in mining and refining. The COVID-19 pandemic initially disrupted silver mining operations globally, reducing supply by approximately 6-8%, while simultaneously accelerating commitments to renewable energy transitions in major economies. The exceptional price spike in 2025, reaching above ₹100,000/kg, reflects a combination of speculative demand, industrial requirements, and supply tightness in global markets.

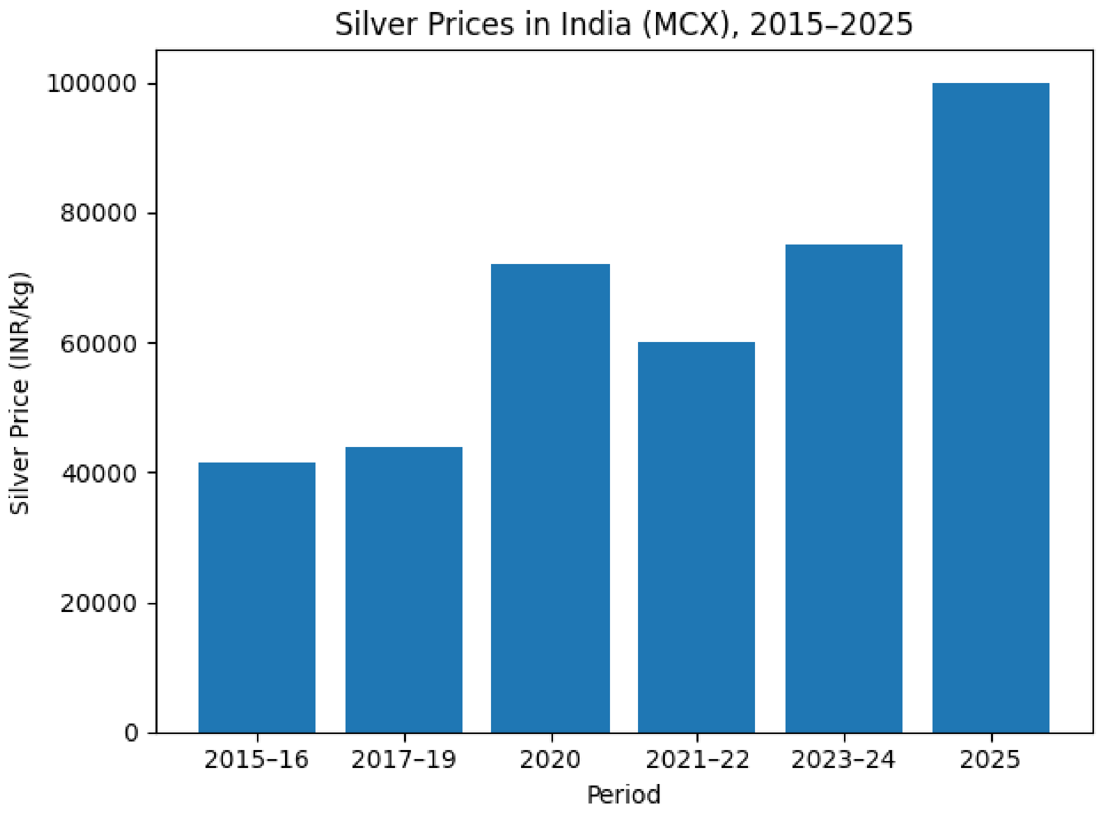

Figure 1 Silver Prices in India (MCX)
Source: Multi Commodity Exchange of India (MCX), author's compilation

4.2 Composition of Silver Demand in India

On the demand side, India remains one of the world's largest consumers of silver, typically ranking second or third globally after China and occasionally the United States. Total annual silver consumption in India has ranged from approximately 6,500 tonnes to 9,500 tonnes during the study period, with usage distributed across jewelry, investment, and industrial applications.

Table 1: Composition of Silver Demand in India, 2015-2025 (in tonnes and percentage)

Year	Jewellery	%	Industrial	%	Investment	%	Total
2015	4,200	62%	1,100	16%	1,500	22%	6,800
2017	4,500	60%	1,400	19%	1,600	21%	7,500
2019	4,300	58%	1,700	23%	1,400	19%	7,400
2021	4,600	56%	2,100	26%	1,500	18%	8,200
2023	4,800	54%	2,600	29%	1,500	17%	8,900
2025	5,000	52%	3,200	33%	1,400	15%	9,600

Source: World Silver Survey (various years), author's compilation

In recent years, the share of industrial demand has increased steadily from 16% in 2015 to 33% in 2025, driven largely by the expansion of solar energy capacity and electronics manufacturing. Within industrial demand, solar PV manufacturing has emerged as the dominant component, accounting for an estimated 55-65% of total industrial silver consumption by 2025. This represents approximately 1,800-2,100 tonnes annually dedicated to solar applications.

Although technological advancements have reduced silver intensity per solar module from approximately 35-40 mg/watt in 2015 to 12-18 mg/watt in 2025, rapid capacity addition has more than offset these efficiency gains, resulting in sustained aggregate demand growth. The absolute quantity of silver required for India's annual solar installations has thus continued to rise despite improving material efficiency.

4.3 India's Import Dependence

India's domestic production of silver is limited, making the country heavily dependent on imports to meet rising demand. Figure 2 illustrates India's silver import dependence ratio over the study period:

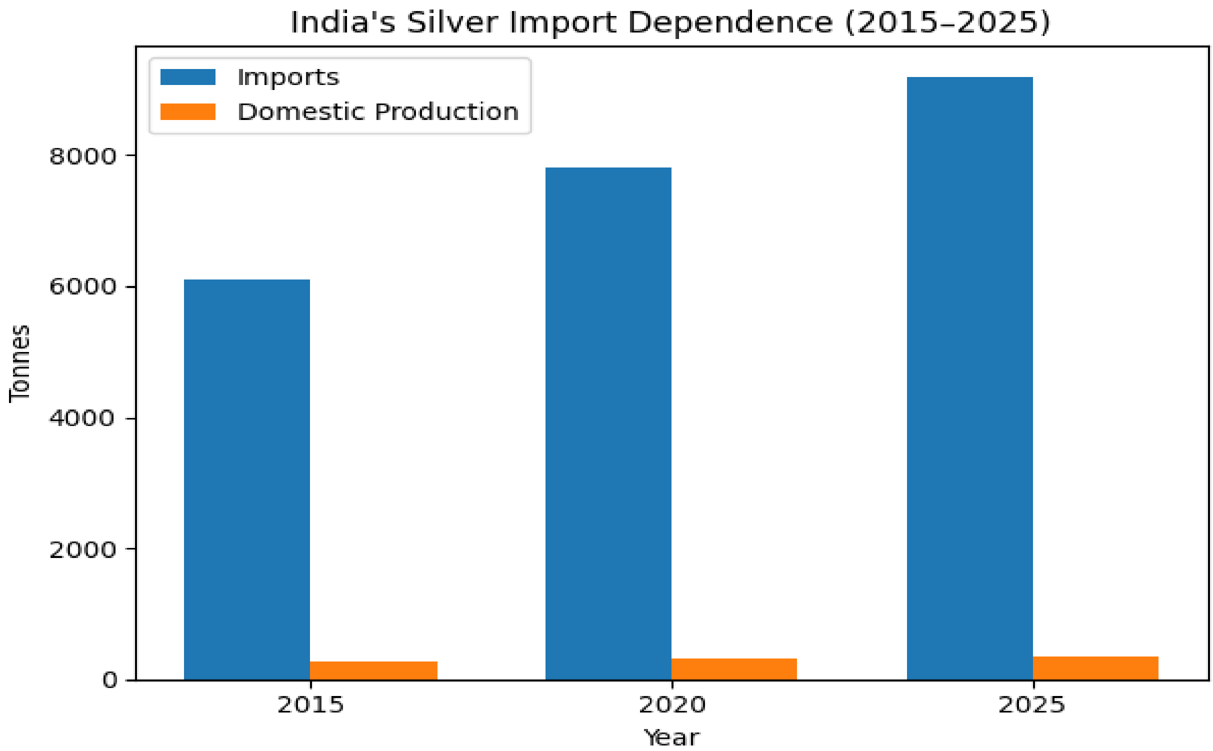

Figure 2. India's Silver Import Dependence

Source: DGCIS, RBI, World Silver Survey, author's calculations

Import data indicate a growing reliance on external sources, with import dependence consistently exceeding 92% throughout the period and reaching 96% in recent years. India's domestic silver production, derived primarily as a by-product of lead-zinc mining operations in Rajasthan and other states, has remained relatively stagnant at 200-350 tonnes annually, insufficient to meet even 5% of domestic demand.

This high import dependence exposes the renewable energy sector to international price volatility and exchange rate movements. When silver prices surge in global markets, Indian importers face compounded effects through both higher commodity prices and potential rupee depreciation. For instance, the 2025 price spike represented a cost increase of over 40% in dollar terms and nearly 45% in rupee terms, directly impacting solar module manufacturing costs.

4.4 Geographic Sources of Silver Imports

Table 2: Major Sources of Silver Imports to India (2024-2025)

Country/Region	Import Volume (tonnes)	Share (%)	Form
South Korea	2,100	22.80%	Refined, semi-finished
UAE	1,850	20.10%	Refined bars, investment
Switzerland	1,400	15.20%	Refined bars, high purity
Australia	950	10.30%	Refined, semi-finished
Peru	720	7.80%	Refined bars
China	680	7.40%	Semi-finished, products
Belgium	540	5.90%	Refined bars
Others	960	10.50%	Various
Total	**9,200**	**100%**	-

Source: DGCIS Trade Statistics, author's compilation

The geographic concentration of imports creates additional supply chain risks, with the top three sources accounting for nearly 60% of total imports. Disruptions in any major source country due to geopolitical tensions, trade policy changes, or economic crises could significantly affect India's silver availability and pricing.

4.5 Implications for Renewable Energy Costs

The observed trends suggest that silver prices and demand in India are increasingly influenced by structural factors linked to the renewable energy transition rather than traditional investment demand alone. As solar energy deployment accelerates, silver is likely to assume greater strategic importance within India's green economy framework.

From a cost perspective, silver represents approximately 4-7% of total solar PV module manufacturing costs under normal price conditions. However, during price spikes, this share can increase to 8-12%, creating significant pressure on module prices and potentially affecting project economics. Given that solar modules constitute 50-60% of total solar project costs, silver price volatility can indirectly influence the overall levelized cost of solar energy and the competitiveness of solar power against conventional alternatives.

4.6 India's Solar Energy Growth Trajectory

Solar energy constitutes the largest share of India's renewable energy expansion and is expected to remain central to achieving national green economy targets. India's installed solar capacity has grown dramatically from approximately 5 GW in 2015 to over 75 GW by the end of 2025, representing a compound annual growth rate (CAGR) of approximately 30% over the decade.

Table 3: India's Solar Capacity: Historical Growth and Future Targets

Year	Installed Solar Capacity (GW)	Annual Addition (GW)	Cumulative Growth
2015	5	2	-
2017	12.8	4.1	156%
2019	28.2	7.8	464%
2021	42.8	7.5	756%
2023	60.4	10.2	1108%
2025	75.3	12.8	1406%

2030 (Target)	**280**		**5500%**

Source: Ministry of New and Renewable Energy (MNRE), IRENA, author's compilation

The government's target of achieving 500 GW of renewable energy capacity by 2030, with approximately 280 GW from solar, implies average annual additions of 35-40 GW of solar capacity during 2026-2030. This represents a significant acceleration from current deployment rates and underscores the scale of material requirements that will accompany this expansion. These trends suggest that material constraints may increasingly shape the feasibility and cost trajectory of India’s solar expansion.

4.7 Silver Intensity in Solar PV Technology

Crystalline silicon photovoltaic (PV) technology, which dominates India's solar installations (>95% market share), relies on silver for electrical contacts due to its superior conductivity and durability. Silver is used primarily in the metallization paste for front-side contacts (fingers and busbars) and increasingly in rear-side contacts in bifacial and PERC (Passivated Emitter and Rear Cell) technologies.

Table 4: Silver Loading per Watt in Solar PV Cells (mg/W)

Year	**Silver Loading (mg/W)**	**% Change from 2015**	**Technology Driver**
2015	38.5	-	Standard screen printing
2017	32	-16.90%	Thinner fingers, reduced paste
2019	24.5	-36.40%	Multi-busbar, finer screen
2021	18.2	-52.70%	Advanced screen printing, PERC
2023	14.8	-61.60%	Dual-printing, seed layer
2025	12.5	-67.50%	Copper plating hybrid, SMBB
2030 (Projected)	8.0-10.0	-74% to -79%	Copper plating, alternative contacts

SMBB: Super Multi-Busbar technology

Source: International Technology Roadmap for Photovoltaic (ITRPV), various editions

Although continuous technological improvements have reduced the quantity of silver used per solar module by approximately 67% over the past decade, the rapid scale of solar deployment has outweighed these efficiency gains. Future projections suggest further reductions to 8-10 mg/W by 2030 through technologies such as copper plating for seed layers, alternative metallization methods, and improved paste formulations. However, complete elimination of silver from mainstream PV technology is not anticipated within the next decade due to technical constraints related to contact resistance, reliability, and manufacturing complexity.

4.8 Comparative Global Context

To contextualize India's position, Figure 3 compares projected solar PV silver demand across major markets:

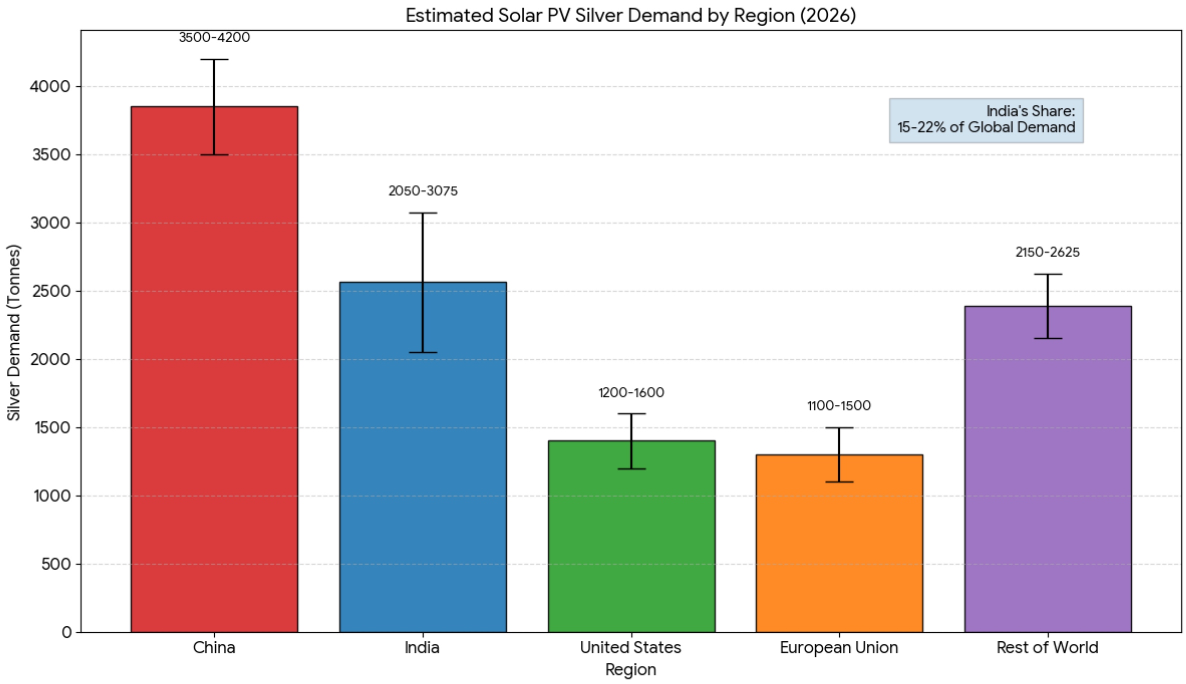

Figure 3: Projected Annual Silver Demand from Solar PV by Country/Region (2030)

Source: Cattaneo et al. (2026), IEA renewable energy projections, author's compilation

India is projected to account for 15-22% of global silver demand from solar PV by 2030, second only to China. This underscores both the scale of India's renewable energy ambitions and the material security challenges that accompany them.

4.9 Material Intensity and Strategic Implications

This growing material requirement poses strategic challenges for India, given its limited domestic silver production and 96% import dependence. Increased reliance on imported silver may elevate project costs and expose the renewable energy sector to global price volatility and supply disruptions. A 10% increase in silver prices, for instance, translates to approximately 0.5-0.8% increase in solar module costs, which can affect project economics at scale.

Consequently, the material intensity of solar energy expansion highlights the need to integrate critical mineral considerations into renewable energy planning. The linkage between solar expansion and silver demand underscores that India's renewable energy transition is not only an energy policy issue but also a resource security concern. Addressing this linkage is essential to ensure the long-term affordability and sustainability of solar-driven green growth.

5. Conclusion

India's renewable energy transition represents a central pillar of its green economy strategy, with solar photovoltaic (PV) deployment playing a dominant role in expanding clean energy capacity. This study demonstrates that silver has become a strategically important material underpinning this transition, reflecting a fundamental shift in its demand profile. Industrial consumption of silver in India has increased substantially over the past decade, driven primarily by solar PV manufacturing, indicating a transition from traditional investment and ornamental uses toward critical industrial applications.

The analysis highlights India's pronounced dependence on imported silver, with domestic production remaining minimal relative to total consumption. This structural reliance creates exposure to international price volatility and potential supply disruptions, posing risks for the cost stability and scalability of renewable energy projects. These risks are compounded by the observed volatility in silver prices, which has intensified in recent years as global demand increasingly reflects clean energy requirements rather than purely financial factors.

Future material requirements further reinforce silver's strategic relevance. Achieving India's solar capacity targets will require sustained silver inputs, adding pressure to already concentrated global supply chains. Despite technological efforts to reduce silver intensity in photovoltaic cells, the metal remains essential for maintaining efficiency and reliability in mainstream PV technologies in the near term. Consequently, material availability emerges as a non-trivial constraint in India's renewable energy planning.

The study also identifies an underdeveloped opportunity in silver recycling. The absence of robust systems for recovering silver from end-of-life solar panels and electronic waste represents a missed avenue for reducing import dependence and advancing circular economy objectives. Strengthening recycling infrastructure and technological capability could partially offset future demand while improving the environmental sustainability of renewable energy expansion.

From a policy perspective, these findings underscore the need to integrate material security considerations into India's renewable energy and green economy frameworks. Treating silver as a strategic input—rather than solely as a traded commodity—has implications for energy planning, mineral governance, industrial policy, and research and development priorities. Coordinated policy action across these domains can help mitigate supply risks and enhance the resilience of the energy transition.

More broadly, the case of silver illustrates a wider challenge facing India's clean energy ambitions: the material foundations of energy systems are as critical as technological and financial factors. Addressing these foundations proactively will be essential to ensuring that resource constraints do not impede the pace or sustainability of India's transition toward a green economy.

5.1 Future Scope of Study

Future research may employ econometric or systems-based modelling to quantify the impact of silver price volatility on renewable energy costs and investment decisions. Cross-country comparative studies, lifecycle assessments of silver recycling in the Indian context, and scenario analyses incorporating emerging photovoltaic technologies would provide deeper insights into material security for energy transitions.

5.2 Limitations of the Study

This study is based on secondary data and adopts a descriptive analytical approach, which limits the ability to establish causal relationships between silver availability, prices, and renewable energy outcomes. Demand estimates rely on current photovoltaic technology assumptions and may not fully capture rapid technological change or substitution possibilities. In addition, data constraints restrict detailed firm-level or project-level analysis.

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