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Assessing the Physical Feasibility of a Solar-Dominant Net-Zero Pathway in India: Electricity Demand, Land Use and Critical Mineral Constraints

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ABSTRACT

India's 2070 net-zero target will require large-scale renewable electricity expansion with solar power expected to play a dominant role. This study assesses whether a solar-dominant pathway remains physically feasible when long-run electricity demand is evaluated alongside land and silver constraints. Using an Autoregressive Distributed Lag (ARDL) model, electricity demand is projected to 2070 under Low, Base and High scenarios, with urbanisation employed as the long-run demand driver and GDP per capita included as a short-run adjustment factor. The projected demand is then converted into solar capacity requirements and evaluated against India's barren-land availability as well as global silver reserves. The analysis shows that Base and High demand pathways require multi-terawatt solar deployment, creating substantial pressure on both land and silver reserves. Sensitivity analysis across solar shares, deployment mixes and PV technologies indicates that shifting part of deployment towards Integrated and Shared-Surface (ISS) solar, along with silver-intensity reduction, can ease constraints, but cannot fully offset very high electricity demand. The study identifies a land-mineral paradox, where higher-efficiency PV technologies provide only limited land savings but can sharply increase silver dependence. The findings highlight the need for demand moderation, integrated solar deployment, material-efficient technologies, and long-term mineral-security strategies in India's energy transition.

Keywords

Net-Zero Feasibility;
Solar PV transition;
Urbanisation and electricity demand;
Land use and critical minerals;
Cross-resource trade-offs;

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1. Introduction

Global decarbonisation requires rapid renewable expansion. As renewables have become cost-competitive

with conventional power, approximately 86% of upcoming generation projects worldwide are now renewable-based [1]. Global non-fossil power capacity must triple by 2030 to support the 1.5°C target [1,2]. India, which houses one-sixth of the global population, is

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Abbreviations

BLOR	Barren Land Occupancy Ratio	CGM	Conventional Ground-Mounted
CUF	Capacity Utilisation Factor	CUSUM	Cumulative Sum
GW	Gigawatt	ISS	Integrated and Shared-Surface
PERC	Passivated Emitter and Rear Contact	PV	Photovoltaic
SHJ	Silicon Heterojunction	SSP	Shared Socioeconomic Pathway
TOPCon	Tunnel Oxide Passivated Contact	TWh	Terawatt-hour

responsible for 7.4% of total carbon emissions [3].

Currently, the energy sector alone contributes about 75.66% of India's total emissions, and power sector emissions are projected to rise significantly in the coming years [4]. Despite this, the actual contribution of renewable energy sources accounts for only 19.51% of the total primary energy generation in the country [5]. India's renewable capacity has expanded steadily over recent decades, although the pace of growth has remained uneven across periods and technologies.

While new coal plant projects have been halted, coal remains the dominant force in the power sector and contributes approximately 75% of total output [6]. In response, India is making substantial efforts through a rapid transition toward low-carbon alternatives to achieve its net-zero target. India also ranks among the leading renewable and solar-capacity markets globally [1,7]. The country is exceptionally well-positioned for solar energy due to its favourable location near the Tropic of Cancer, offering an annual potential of up to 5,000 trillion kWh.

Technological advancements have made solar PV increasingly affordable, with the weighted average Levelized Cost of Energy (LCOE) dropping by 90% between 2010 and 2024 [8,9]. Rooftop schemes such as PM Surya Ghar have also expanded public participation in solar deployment [10]. These efforts support India's COP26 commitments and its 500 GW renewable-capacity target for 2030 [11,12]. Beyond residential rooftop programmes, long-term solar planning may also require commercial rooftops, building-integrated PV, parking canopies, agrivoltaics and floating solar to reduce dependence on conventional ground-mounted deployment.

However, the transition is shaped by structural economic and demographic change. Urbanisation is expanding at a remarkable pace and is steadily reshaping national electricity requirements as cities become hubs of economic activity [13]. Long-term assessments suggest India is on track to become one of the world's largest

economies, and this anticipated growth will likely raise power demand as rising incomes lead to energy-intensive lifestyles [14].

At the same time, climate-related vulnerabilities may affect productivity, with projections suggesting a potential GDP loss of up to one-quarter by 2070 [15]. The long-run scenario modelling of the OECD also shows that emerging economies will experience sustained structural pressures, making credible forecasting essential for energy planning [16]. Such expansion at this magnitude makes long-term electricity demand estimation central to any realistic transition strategy.

2. Literature Review

Existing literature shows that income growth, urbanisation and regional inequality shape India's electricity demand as households shift from traditional fuels to electricity [17]. Demographic projections demonstrate that different urban growth pathways can produce large variations in future demand [18]. Macro-econometric and machine-learning studies also examine links among renewable adoption, energy use and emissions [19,20]. Assessments argue that development compatible with net-zero will require large-scale electrification of transport, industry, and services [21,22]. Furthermore, industrial growth, behavioural change, and policy reform together determine the scale and timing of decarbonisation [23].

Indian electricity-demand studies have used ARDL, regression, black-box, LSTM and ARIMA approaches across different horizons and scales [24-28]. These studies underscore the need for models that combine structural drivers with robust dynamic adjustment. The selection of GDP per capita and urbanisation as drivers is well-grounded, as they reflect income growth, industrial activity, and structural transformation such as vertical housing and cooling demand [13].

As energy systems modernize, electricity serves as the common carrier replacing direct fossil fuel use in electric mobility and digital infrastructure [16]. Consequently,

long-term electricity consumption is a suitable proxy for aggregate energy demand in a net-zero future. Beyond demand, solar expansion must operate within real land constraints. Rooftop systems, building-integrated PV and other shared-surface approaches can reduce dependence on conventional ground-mounted deployment while contributing additional capacity [29,30].

System-level studies show that site selection and grid flexibility are essential for large-scale deployment [31,32]. Previous analysis finds that access to non-farm barren land and declining module costs drive solar growth, though poorly planned solar parks may displace cropland [33,34]. Agrivoltaics and shared-land models have been suggested as ways to reduce pressure on dedicated land, yet studies reveal that many solar farms continue to occupy former agricultural areas [35,36]. National reports stress that land planning, mineral supply chains, and grid readiness must be aligned [37].

Advances in photovoltaic technology, such as tandem and bifacial configurations, are reaching efficiencies above 30%, which provides some relief to space requirements. However, these advancements do not fully resolve the challenges posed by land scarcity and critical mineral constraints, especially silver, which remains a key input in most commercial panels [38]. Rapid deployment could strain reserves of copper, nickel, cobalt, and especially silver [39].

India is particularly exposed to import-dependent mineral supply chains for modules and batteries [40]. Domestic silver reserves are limited relative to potential demand, and processing is often geographically concentrated and subject to trade risks [41]. Policy discussions explore recycling and circular economy strategies, yet quantitative links between demand and specific mineral requirements remain underdeveloped [42,43].

Although the literature provides useful insights into demand, land and minerals, these dimensions remain weakly integrated in India-specific net-zero analysis. Existing demand models hardly translate electricity projections into solar capacity and associated land pressure; land-use studies do not systematically link spatial requirements with material intensity; and mineral studies often examine scarcity without connecting silver demand to demand-driven solar deployment pathways.

While some integrated assessments exist outside India, they usually treat critical minerals as a broad category rather than quantifying silver-specific constraints under alternative PV technologies [44,45]. In the Indian context, existing studies remain fragmented:

demand projections are rarely translated into solar-capacity requirements, land-pressure estimates are seldom linked with material intensity, and mineral constraints are not systematically assessed under demand-driven solar deployment pathways. This leaves the physical feasibility of India's 2070 solar-dominant pathway underexamined from an integrated demand-land-mineral perspective. The novelty of this study lies in linking ARDL-based electricity-demand projections with solar-capacity requirements, barren-land constraints and technology-specific silver demand pressure. In doing so, it moves the land-mineral trade-off from a general concern to an India-specific quantitative feasibility assessment.

3. Methodology

This section presents the analytical framework used to evaluate the feasibility of a solar-dominant electricity pathway for India. It outlines the demand forecasting methodology, scenario design, econometric validation procedures, and the framework used to translate electricity demand into solar capacity, land requirements, and mineral constraints.

3.1 Framework for Demand Projection and Feasibility Study

This study tests the physical feasibility of a solar-dominant electricity pathway for India up to 2070 by incorporating realistic land and critical mineral constraints. The analysis follows three sequential stages, shifting the focus from conventional cost-optimisation to physical feasibility. First, India's aggregate electricity consumption is projected to 2070 using an Autoregressive Distributed Lag (ARDL) model estimated with annual data from 1971 to 2024. The model captures the long-run relationship between electricity demand and key macroeconomic drivers, providing the demand baseline for assessing whether solar-led decarbonisation remains feasible once spatial limits and mineral requirements are explicitly considered.

The model uses GDP per capita to capture short-run adjustment and urbanisation to represent long-run structural demand. These drivers reflect income growth, dense housing, cooling demand and infrastructure expansion. Their future paths are taken from the Shared Socioeconomic Pathway (SSP) database to generate Low, Base and High demand scenarios. Solar capacity is calculated from projected demand using the assumed

solar share, annual operating hours and Capacity Utilisation Factor (CUF). Land feasibility is then assessed by comparing the land needs of conventional ground-mounted solar with India's barren and unculturable land, while mineral feasibility is assessed by comparing implied silver demand with global reserve benchmarks.

3.2 ARDL Demand Model Specification

The ARDL model is specified in log-log form so that coefficients can be interpreted as elasticities. The long-run relationship is expressed in Eq. (1):

$$\ln(ELEC_CONS_t) = \alpha + \beta_1 \ln(URB_t) + \beta_2 \ln(GDP_t) + \varepsilon_t \quad (1)$$

Here, electricity consumption, urbanization and GDP per capita are expressed in natural logarithms, with urbanisation measured as the percentage of population living in urban areas. The urbanisation coefficient therefore represents the long-run elasticity of electricity demand with respect to urbanisation. Lag length is selected using the Schwarz Information Criterion (SIC), which is suitable for small samples [46]. The ARDL model is then expressed in error-correction form, where the ECT captures adjustment back to the long-run path. Both GDP per capita and urbanisation enter the estimated long-run relationship, although only urbanisation is

statistically significant in the long run. GDP per capita mainly contributes to the short-run dynamics.

3.3 Data and Scenario Design

The empirical base utilises annual data from 1971 to 2024 for electricity consumption, GDP per capita, and urbanisation [47,48,49]. Projections for the exogenous variables are taken from the IIASA SSP database using SSP1, SSP2, and SSP3 to define alternative socioeconomic futures [50]. These pathways generate High, Base, and Low electricity-demand projections through the estimated ARDL model. This keeps the forecast assumptions internally consistent rather than relying on arbitrary growth rates.

3.4 Model Diagnostics

For the ARDL framework to be credible, the series should be integrated of order one, a well-defined long-run relationship must exist, and the residuals must behave well with stable parameters. As shown in Table 1, unit root tests confirm that log electricity consumption, log GDP per capita, and log urbanisation are non-stationary in levels but become stationary after first differencing. This I(1) behavior justifies the application of the ARDL bounds testing approach for cointegration [51].

Table 1: ADF unit root tests for stationarity

Parameter	Statistic	p value	Inference
ELEC_CONS, level	-3.481	0.0529	Do not reject H_0
ELEC_CONS, first difference	-4.855	0.0013	Reject H_0 ; series is stationary in first difference
GDPpc, level	-2.293	0.4303	Do not reject H_0
GDPpc, first difference	-8.073	0.0000	Reject H_0 ; series is stationary in first difference
URB, level	-3.110	0.1149	Do not reject H_0
URB, first difference	-4.451	0.0043	Reject H_0 ; series is stationary in first difference

Note. H_0 denotes the null hypothesis of a unit root.

In the model, urbanisation appears in the long-run relationship while GDP per capita is treated as a short-run driver. The bounds test yields an F-statistic of 4.59 which is above the upper bound for finite-sample critical values and allows us to reject the null of no long-run relationship. This confirms a cointegrating relationship where the estimated long-run elasticity is positive and

statistically significant, indicating that sustained urbanisation is associated with more than proportionate increases in aggregate electricity consumption.

The associated error-correction term is negative and highly significant with a coefficient of approximately -0.10, implying that 10% of any deviation from the long-run equilibrium is corrected each year. Short-run

coefficients on GDP per capita changes are positive, showing that income growth strengthens short-term demand. Further, the Table 2 also shows the residual diagnostics including tests for serial correlation, heteroskedasticity, and normality further support the

specification and reduce concerns about misspecification. Parameter stability is confirmed by CUSUM and CUSUM of squares tests shown in Figure 1 where cumulative sums remain within significance bands throughout the sample period.

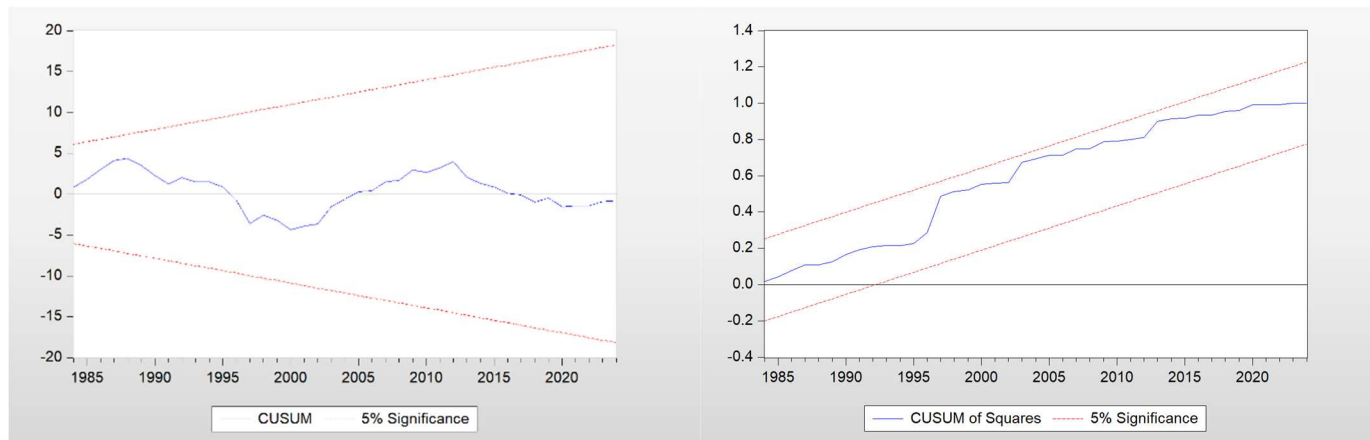


Figure 1: Stability tests for ARDL Model

Table 2: Cointegration, dynamic adjustment and residual diagnostics

Component	Test or parameter	Statistic	p value / critical bounds	Inference
ARDL bounds test	F statistic	4.59	10% finite-sample bounds ($k = 2$): $I(0) = 3.33$; $I(1) = 4.31$	F statistic exceeds 10% upper bound; cointegrating relationship confirmed at 10% level
Long run coefficients	$\ln(\text{URB})$	4.97	0.01	Long run elasticity of urbanisation large and highly significant
Error correction term	$\text{ECT}(-1)$	-0.102	0.0058	Error correction term negative and highly significant; about 10.2% of disequilibrium removed each year
Residual diagnostics	Breusch-Godfrey LM (serial correlation)	2.65	0.08	Fail to reject H_0 of no serial correlation; residuals free from autocorrelation
	Breusch-Pagan-Godfrey (heteroskedasticity)	1.86	0.09	Fail to reject H_0 of homoskedasticity; no evidence of unconditional heteroskedasticity
	ARCH LM	0.60	0.44	Fail to reject H_0 of no ARCH effects; no evidence of conditional heteroskedasticity
	Jarque-Bera	0.50	0.78	Fail to reject normality; residuals are normally distributed
	Ramsey RESET	1.01	0.32	No evidence of functional-form misspecification

3.5 Forecast Validation

Short-run predictive performance is checked because land and mineral results depend directly on projected

demand. In-sample forecast statistics for 2015 to 2024 show that the model tracks actual consumption very closely as evidenced by low error metrics such as a MAPE of 0.54%. The results from Table 3 provide a

strong econometric basis for using the ARDL model for long-horizon projections up to 2070.

Table 3: In-sample forecast accuracy for the ARDL model

Metric	Value
Root Mean Squared Error (RMSE)	0.0416
Mean Absolute Error (MAE)	0.0386
Mean Absolute percentage Error (MAPE)	0.54%
Theil Inequality Coefficient	0.0029

3.6 Translating Demand Projections into Solar Capacity

The capacity estimation connects the econometric demand projections, expressed in TWh, to the amount of solar capacity required in GW. This step is essential because land and mineral constraints are defined in terms of installed solar capacity rather than annual consumption. After converting the log forecasts back into level form, the required solar generation in 2070 is first estimated under a central specification in which solar accounts for 60% of total electricity generation in each demand scenario. The corresponding solar capacity is then computed using the standard formula as depicted in Eq. (2):

$$\text{Solar capacity} = \left\{ \frac{\text{Annual solar generation} \times 1000}{8760 \times \text{CUF}} \right\} \quad (2)$$

The choice of a 60% solar share in 2070 is grounded in national net-zero modelling rather than an arbitrary decision. It is aligned with the net-zero 2070 scenario developed by the Council on Energy, Environment and Water (CEEW), in which the energy mix in 2070 is solar-dominant, with a substantial wind contribution and a smaller share of other energy sources [52]. To translate this capacity mix into generation share, the study applies technology-specific capacity utilisation assumptions. Solar capacity is estimated using a time-varying CUF.

Although the average solar CUF in India can reach around 20% under favourable conditions, this study adopts a conservative 15% value for 2025 to account for weather variability, land-slope conditions, dust and soiling losses, and regional irradiance differences [53-55]. For the analysis, the average CUF is assumed to rise gradually from 15% in 2025 to 30% by 2070, effectively doubling over the forecast horizon, reflecting expected improvements in module efficiency, plant design, and operational performance [53-55]. Using the CEEW capacity mix together with these CUF assumptions and the residual coal and bioenergy shares, the implied solar

contribution is estimated at about 58-59% of total electricity generation in 2070 [52].

For such long horizon scenarios, it is more realistic to work with rounded values rather than very precise numbers, so this analysis represents the estimated 58-59% range as a rounded 60% central solar-share assumption. This value is also strongly supported by the modelling evidence, since the same study reports solar shares rising to about 70 to 72 per cent by 2100 in net-zero pathways [52]. However, the analysis does not rely solely on this central value.

To examine whether the results are sensitive to this assumed solar share, the study further introduces two sensitivity cases with solar contributing 50% and 70% of electricity generation in 2070, representing a ± 10 percentage-point deviation from the central 60% assumption. This sensitivity check ensures that the feasibility conclusions are not driven by a single solar-share assumption, but remain robust across a realistic range of solar-based net-zero transition.

3.7 Land-Use and Mineral Feasibility Framework

Spatial feasibility is assessed by estimating the land requirement of the solar deployment share that relies on conventional ground-based installation [56]. It is estimated by introducing two land-accounting categories: Conventional Ground-Mounted (CGM) Solar, and Integrated and Shared-Surface (ISS) Solar. CGM solar refers to conventional PV requiring exclusive ground occupation and is counted against the barren-land benchmark. ISS solar refers to deployment pathways that reduce exclusive ground occupation, including rooftop and building-integrated PV, agrivoltaics and floating solar. Existing estimates indicate substantial technical potential across these ISS components.

India Residential Energy Survey (IRES) based assessment of CEEW estimates India's residential rooftop technical potential at 637 GW under the household and roof-stock conditions captured in the 2020 survey [57]. CEEW also reports India's floating solar potential at about 207 GW [58]. Further, a GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) estimate places India's agri-photovoltaic technical potential between 3,156 GW and 13,803 GW, reflecting the large agricultural land base available for shared-use solar deployment [59]. These estimates are not summed together as they differ in method, geography and deployability. They are used only to support ISS as a plausible spatial-diversification category under present

technical-potential estimates, not as a fixed 2070 technical-potential estimate.

Two configurations are examined: Case A with 80% CGM and 20% ISS, and Case B with 60% CGM and 40% ISS. CGM solar requires 20.24 km² per GW, while ISS solar is treated as ground-land-neutral because it uses existing built surfaces and does not directly occupy barren or unculturable land [60]. ISS deployment still remains constrained by several factors such as roof suitability, agricultural compatibility, water-body suitability, ecological concerns, financing, consumer uptake and grid readiness [9]. Hence, the ISS shares used in the sensitivity analysis are treated as bounded policy cases rather than freely scalable assumptions.

India's 171,680 km² of barren and unculturable land is used as the national benchmark for assessing spatial feasibility [61]. The key indicator is the Barren Land Occupancy Ratio (BLOR), which measures the percentage of this available barren land that would be required for CGM solar deployment. A higher BLOR indicates greater pressure on the national barren-land benchmark, while a value above 100% shows that the estimated CGM solar land requirement exceeds this broad benchmark before applying stricter site-suitability exclusions. It is calculated as shown in Eq. (3):

$$\text{BLOR} = \left\{ \frac{\text{CGM solar land requirement}}{\text{Total barren and unculturable land}} \right\} \times 100 \quad (3)$$

The BLOR framework is used here as a national-level estimate of spatial pressure, not as a detailed site-suitability assessment. It does not exclude protected areas, defence lands, water bodies, vegetation, settlements, slope restrictions, transmission access or other local siting constraints. Since these exclusions would reduce the land practically available for CGM solar, the reported BLOR values should be interpreted as conservative indicators of land pressure under a broad land-availability benchmark, not as estimates of actually deployable solar land. Once real siting restrictions are considered, effective land pressure is likely to be higher.

Material feasibility focuses on silver, an essential component of commercial solar panels that directly constrains capacity expansion [62]. As shown in Table 4, silver is not the only material concern in solar PV; copper and polysilicon also involve important supply-chain risks. However, silver is prioritised because it is directly used in PV cell metallisation, varies across PV technologies, and most clearly reflects the land-mineral trade-off examined in this study.

Table 4: Rationale for Focusing on Silver

Material	Role in solar PV	Main constraint	Relevance to this study
Silver	Cell metallisation and electrical contacts in crystalline-silicon PV cells	Geological scarcity, reserve pressure, and technology-specific intensity	Most directly captures the land-mineral trade-off, as some high-efficiency PV modules require higher silver use per GW to reduce land needs
Copper	Module interconnects, cables, inverters, transformers, and grid integration	Mining-capacity pressure from wider electrification demand	Important for the broader power system, but less specific to the module-efficiency and land-footprint trade-off
Polysilicon	Base material for most crystalline-silicon PV modules	Refining concentration and geopolitical supply-chain dependence	Strategically important for India's solar manufacturing security, but the main constraint is processing concentration rather than geological scarcity

While copper constraints arise mainly from wider electrification demand and polysilicon risks from refining concentration, silver is more directly linked to the material intensity of land-saving PV pathways. Although copper-based metallisation is considered a potential substitute for silver, its commercial-scale adoption still faces technical challenges such as contact oxidation, copper diffusion, process complexity, and manufacturing reliability concerns [63-65]. Therefore, silver is used as the focal material for quantitative feasibility analysis, with global reserves serving as the benchmark given India's limited domestic reserves and

import dependence.

Silver intensity for mainstream Passivated Emitter and Rear Cell (PERC) technology is approximately 15.4 tonnes per GW, though newer designs such as Tunnel Oxide Passivated Contact (TOPCon) and Silicon Heterojunction (SHJ) require significantly higher amounts, like 25.6 and 33.9 tonnes per GW, respectively [62]. Even if intensities were to halve by 2070, the Base and High demand scenarios would still necessitate substantial silver volumes [66].

Scenario-specific silver requirements are estimated by applying the baseline silver intensity coefficient to the

projected solar capacity and comparing the resulting estimates with the global reserve benchmark of 610,000 tonnes to assess geological feasibility [67]. Although the current estimate of 610,000 tonnes of global silver reserves may increase in the future through new discoveries and improved extraction, this study uses the present reserve estimate as the benchmark for assessing binding silver constraints.

4. Results and Discussion

This section presents the results of the analysis and discusses their implications for India's solar-dominant transition. It examines the role of urbanisation in shaping electricity demand, the resulting solar capacity requirements, spatial feasibility under alternative deployment configurations, and the implications of critical mineral constraints.

4.1 Urbanisation as the Structural Demand Engine

The ARDL results show that urbanisation is the main long-run structural driver of electricity demand. The

estimated elasticity of 4.97 is statistically significant, indicating that sustained urbanisation raises electricity use more than proportionately. This reflects changes in housing form, cooling demand, service-sector activity and electrified urban transport. GDP per capita is retained as a short-run driver, capturing macroeconomic adjustment without overloading the long-run equation. The result implies that India's city-building pattern will strongly influence future electricity needs, making demand-side measures such as efficient buildings, cooling standards and compact urban planning essential to feasibility.

4.2 Demand Scenarios and Solar Capacity Needs

Figure 2 shows three diverging electricity demand paths for 2025-2070 based on the SSP-linked income and urbanisation assumptions. In the figure, the horizontal axis represents the years, while the vertical axis reports projected annual electricity demand in terawatt-hours (TWh).

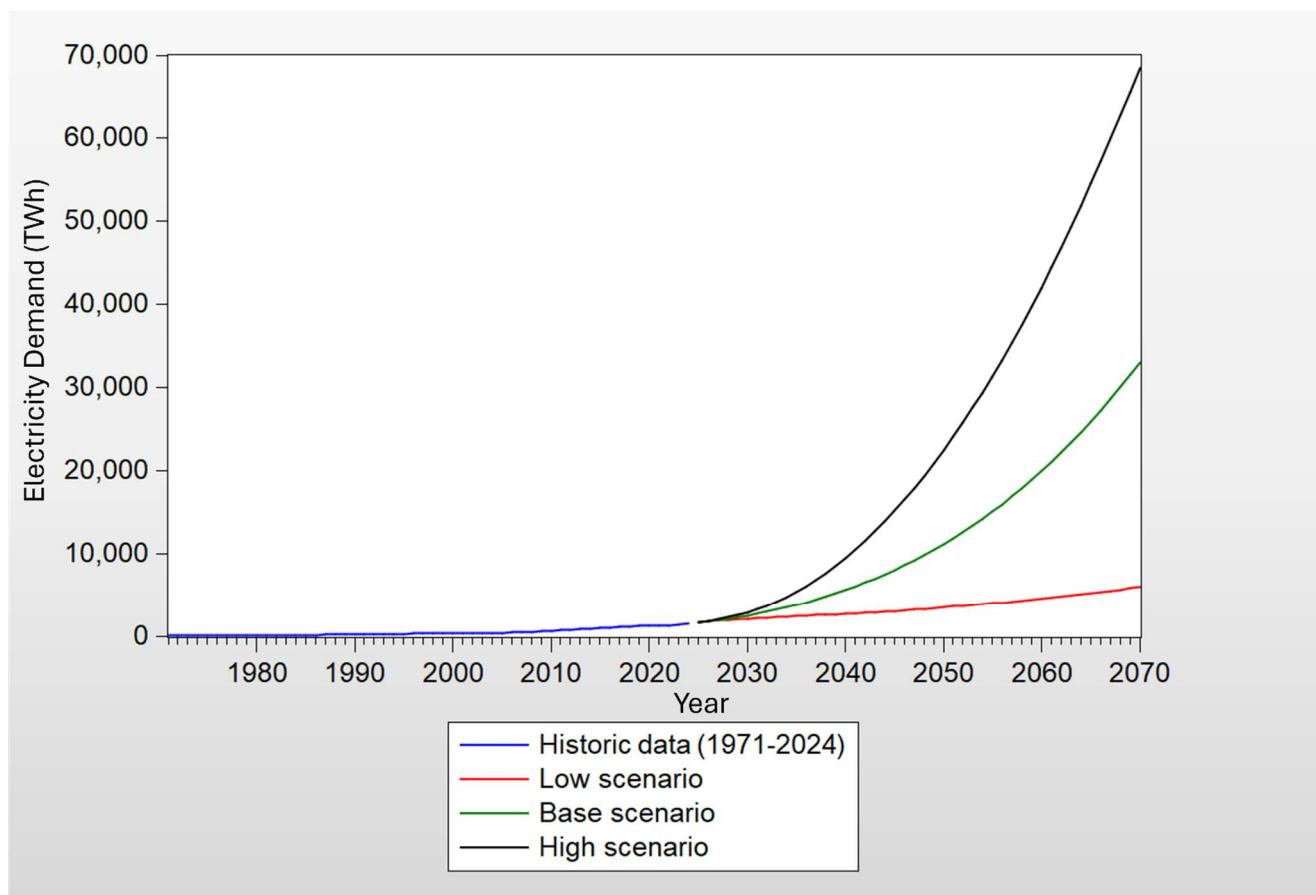


Figure 2: Electricity demand projections using the ARDL model.

Compared with the historical trend, the Base and High scenarios illustrate the scale of demand growth that could emerge under rapid structural transformation. By 2070, electricity demand reaches 6,000 TWh in the Low scenario, 33,000 TWh in the Base scenario, and 69,000 TWh in the High scenario. Based on the earlier methodological discussions, Table 5 translates these demand levels into multi-terawatt solar capacity requirements, which are later divided into CGM and ISS shares to assess their implications for BLOR.

The solar-share sensitivity confirms the same pattern. At 50% solar share, capacity still reaches about 6,200 GW in the Base scenario and 13,000 GW in the High scenario; at 70%, it rises to about 8,700 GW and 18,000 GW. Thus, the challenge is not driven by a single 60% assumption.

Table 5: Projected 2070 electricity demand and implied solar capacity requirements

Assumed solar share (%)	Forecast Scenario	Electricity demand (TWh)	Required solar capacity (GW)
60%	Low	6,000	1,250
	Base	33,000	7,500
	High	69,000	15,500
50%	Low	6,000	1,000
	Base	33,000	6,200
	High	69,000	13,000
70%	Low	6,000	1,500
	Base	33,000	8,700
	High	69,000	18,000

4.3 Spatial Feasibility

Table 6 presents the spatial feasibility results under alternative solar-share assumptions, CGM-ISS deployment configurations and PV technology cases. The results show that deployment structure strongly influences the land footprint of India's solar-dominant pathway. Under the central 60% solar-share case, PERC-based CGM deployment in Case A requires about 120,500 km² in the Base scenario and 251,500 km² in the High scenario. The corresponding BLOR values are 70% and 147%.

This indicates that the High-demand pathway would exceed the national barren-land benchmark if the transition remains strongly CGM dependent, even before accounting for realistic operational exclusions such as protected areas, vegetation, defence lands and grid-

access constraints. Therefore, the operational land constraint is likely stronger than the reported BLOR values suggest, because actual project-level siting would further reduce the land available after environmental, physical and grid-access exclusions.

To reflect technology-related land savings, the study derives technology-adjusted land coefficients using reported energy-yield gains over PERC [68]. Since direct land-use coefficients for PERC, TOPCon and SHJ are not consistently reported, the adjustment is made using an inverse proportional relationship between energy yield and land requirement as shown in Eq. (4):

$$L_i = \frac{L_{PERC}}{1+g_i} \quad (4)$$

where L_i is the adjusted land coefficient for technology i , L_{PERC} is the baseline PERC land coefficient, and g_i is the reported energy-yield gain over PERC. This is not treated as a site-specific land-use measurement, but as a yield-adjusted estimate showing how higher energy output can reduce land need per unit of electricity generated.

The technology-specific rows in Table 6 show that land requirement declines modestly from PERC to TOPCon and SHJ. For example, under the central 60% solar-share Base scenario in Case A, land requirement falls from about 120,500 km² under PERC to 114,000 km² under TOPCon and 110,500 km² under SHJ. A similar pattern is seen in Case B, where the corresponding land requirement declines from 90,500 km² under PERC to 85,500 km² under TOPCon and 83,000 km² under SHJ. However, the land saving remains relatively small, showing that technology improvement alone cannot resolve the spatial constraint without the expansion of ISS deployment and demand moderation.

The sensitivity cases confirm that the land constraint is not driven only by the central 60% solar-share assumption. Even under the lower 50% solar-share case, the High scenario continues to place heavy pressure on available barren land. At the higher 70% solar-share case, land pressure becomes more severe across all technologies. Although TOPCon and SHJ reduce land requirement relative to PERC, the High-demand pathway remains spatially constrained, especially under Case A.

Case B reduces land pressure by increasing the ISS deployment share. Since ISS solar falls outside the barren-land denominator, it lowers the share of capacity that must be met through CGM deployment. However, ISS deployment has its own limitations, as it depends on roof suitability, ownership patterns, farmer and consumer

uptake, ecological constraints and grid integration [9]. but cannot fully offset very high electricity demand. Therefore, ISS expansion can relax the BLOR constraint,

Table 6: Land Requirements and BLOR under Alternative Solar-Share and Deployment Scenarios in 2070

Solar PV Technology	Assumed solar share (%)	Forecast Scenario	Case A		Case B	
			Land Required (km ²)	BLOR (%)	Land Required (km ²)	BLOR (%)
PERC	60%	Low	20,500	12	15,000	9
		Base	120,500	70	90,500	53
		High	251,500	146	188,500	110
	50%	Low	16,500	10	12,500	7
		Base	100,000	58	75,000	44
		High	209,500	122	157,000	91
	70%	Low	24,000	14	18,000	10
		Base	141,000	82	105,500	61
		High	294,000	171	220,500	128
TOPCon	60%	Low	19,500	11	14,500	8
		Base	114,000	66	85,500	50
		High	238,500	139	179,000	104
	50%	Low	16,000	9	12,000	7
		Base	95,000	55	71,000	41
		High	198,500	116	149,000	87
	70%	Low	23,000	13	17,000	10
		Base	133,500	78	100,000	58
		High	278,500	162	209,000	122
SHJ	60%	Low	18,500	11	14,000	8
		Base	110,500	64	83,000	48
		High	231,000	135	173,500	101
	50%	Low	15,500	9	11,500	7
		Base	92,000	54	69,000	40
		High	192,500	112	144,500	84
	70%	Low	22,000	13	16,500	10
		Base	129,500	75	97,000	57
		High	270,000	157	202,500	118

Note. Case A assumes 80% CGM and 20% ISS, while Case B assumes 60% CGM and 40% ISS. Only CGM solar is counted in the BLOR calculation. ISS solar includes rooftop solar, building-integrated PV, agrivoltaics and floating solar, and is treated as outside the barren-land denominator rather than as land-neutral.

In practice, India's solar strategy will require a balanced portfolio rather than dependence on conventional ground-mounted solar alone. Built-surface and shared-surface options, including residential, commercial and institutional rooftops, building-integrated PV, parking canopies, agrivoltaics and floating solar, should therefore be integrated into municipal building codes, industrial-estate planning, public-building programmes and site-specific solar planning [69,70]. Schemes such as PM Surya Ghar Muft Bijli Yojana can support the residential rooftop deployment, but the broader ISS pathway would also require commercial rooftops, building-integrated PV,

agrivoltaics and floating solar to be integrated into long-term spatial planning.

4.4 Material Feasibility

Mineral constraints become serious even when land appears manageable, and this pressure varies substantially with the photovoltaic technology assumed. To avoid treating silver intensity as a single fixed coefficient, Table 7 reports silver requirements under three technology cases: 15.4 tonnes/GW for PERC, 25.6 tonnes/GW for TOPCon, and 33.9 tonnes/GW for SHJ [62]. These cases are not used as predictions of future

technology shares, but as material-intensity bounds that show how technology choice can alter the feasibility of a solar-based transition.

As shown in Table 7, silver demand varies sharply depending not only on the solar share assumed, but also on the photovoltaic technology used to deliver that capacity. Even under the central 60% solar-share case and the relatively conservative PERC assumption, silver requirements reach 115,000 tonnes in the Base scenario and 239,000 tonnes in the High scenario.

These values correspond to approximately 19% and 39% of current global silver reserves, respectively [62]. This is already a very large claim on a mineral that is required across several competing sectors. Although global reserve estimates may expand over time through new discoveries, improved extraction technologies, or reclassification of resources, such future expansion cannot be assumed to automatically match the scale and timing of solar-sector demand.

Table 7: Silver Requirements under Alternative Solar-Share and PV Technology Scenarios in 2070

Solar share	Forecast scenario	Solar capacity 2070 (GW)	PERC		TOPCon		SHJ	
			Silver requirement (tonnes)	Global reserve share (%)	Silver requirement (tonnes)	Global reserve share (%)	Silver requirement (tonnes)	Global reserve share (%)
60%	Low	1,250	19,000	3	32,000	5	43,000	7
	Base	7,500	115,000	19	190,000	31	252,000	41
	High	15,500	239,000	39	398,000	65	527,000	86
50%	Low	1,000	16,000	3	26,000	4	35,000	6
	Base	6,200	95,000	16	158,000	26	210,000	34
	High	13,000	199,000	33	331,000	54	439,000	72
70%	Low	1,500	23,000	4	38,000	6	50,000	8
	Base	8,700	134,000	22	223,000	37	295,000	48
	High	18,000	280,000	46	465,000	76	615,000	101

The pressure becomes much sharper when newer high-efficiency technologies are considered. Under TOPCon, the Base and High scenarios require 190,000 tonnes and 398,000 tonnes of silver, equivalent to 31% and 65% of current global reserves. Under SHJ, the same scenarios rise to 252,000 tonnes and 527,000 tonnes, corresponding to 41% and 86% of global reserves. This shows that the silver constraint is not simply a result of assuming a high solar share; it is also strongly shaped by the material intensity of the technology pathway chosen. In other words, a technology that improves conversion efficiency and reduces land pressure may still worsen the mineral constraint if it requires more silver per GW of installed capacity.

The sensitivity cases also support this finding. Even when the solar share is reduced to 50%, the High scenario requires 199,000 tonnes under PERC, 331,000 tonnes under TOPCon, and 439,000 tonnes under SHJ. At the 70% solar-share case, the High scenario rises to 280,000 tonnes under PERC, 465,000 tonnes under TOPCon, and 615,000 tonnes under SHJ. In the most demanding case, the estimated silver requirement exceeds current global

silver reserves. Allocating such a large fraction of global silver reserves exclusively to India's solar PV deployment would therefore be geologically and economically impractical, especially given its competing uses in electronics, electrical equipment, jewellery, and other industrial applications.

Comparison with India's domestic reserves of 7,000 tonnes highlights an even severe restriction, as requirements even in the Low scenario are many times higher than available domestic stock. This gap becomes more severe under TOPCon and SHJ assumptions, where higher silver intensity raises material requirements without changing the underlying electricity-demand pathway. India already relies heavily on imported silver to meet its industrial demand, and future large-scale solar deployment would further increase this dependence unless technological advancements substantially reduce silver intensity.

Viewed from the opposite direction, these results also indicate the material ceiling beyond which solar expansion becomes difficult. If only a limited share of global silver reserves could realistically be allocated to

India's solar sector, the feasible solar capacity would fall sharply as silver intensity rises from PERC to TOPCon and SHJ. Thus, Table 7 should be interpreted not only as an estimate of silver demand, but also as a reality check on the maximum solar capacity that can be supported before silver becomes a binding constraint.

These considerations show that solar feasibility cannot be assessed only through land availability or installed-capacity targets. Beyond a certain level of deployment, the transition becomes constrained by global resource availability and competing material demands. If multiple countries pursue similar high-solar, high-demand pathways using comparable technologies, the world as a whole may face a collective scarcity problem.

The magnitudes reported in Table 7 therefore highlight the need to treat silver availability as a core design parameter in long-term solar strategies rather than as a secondary factor. They also point to a deeper structural tension in the transition, where technological attempts to economise on land can simultaneously intensify pressure on critical mineral reserves.

4.5 Integrated Policy-Sensitivity Analysis and the Land-Mineral Paradox

To move from constraint identification to policy feasibility, Table 8 combines three response margins: demand pathway, CGM-ISS deployment mix and silver-intensity reduction. The exercise uses the central 60% solar-share pathway and compares three policy cases: 80:20 CGM-ISS with no silver reduction, 70:30 CGM-ISS with 25% silver reduction, and 60:40 CGM-ISS with 50% silver reduction. The 80:20 case is treated as a conservative spatial-diversification case, recognising that ISS expansion is constrained by building suitability, agricultural compatibility, water ecosystem concerns, financing, consumer uptake and grid readiness. The 70:30 case represents a moderate policy case, while the 60:40 case represents a stronger, aspirational mitigation case. These assumptions are not forecasts, but bounded sensitivity cases used to test whether progressively greater ISS deployment and silver-thrifting can relax the land-mineral constraint.

The value of Table 8 lies in converting the land-mineral trade-off from a broad conceptual concern into measurable feasibility thresholds across demand pathways, CGM-ISS deployment mixes and PV technologies. Table 8 shows that the most feasible pathway is the Base-demand pathway combined with a

60:40 CGM-ISS deployment mix and a 50% reduction in silver intensity by 2070. In practical terms, this implies keeping electricity demand closer to the Base pathway of 33,000 TWh by 2070, corresponding to an average annual demand growth of about 6.5% from the 2025 baseline. It also requires expanding the ISS deployment to about 3,000 GW out of the 7,500 GW solar requirement, while reducing silver use per GW by half.

Under this combination, BLOR remains below 100% across PERC, TOPCon and SHJ, while silver demand remains within the 15-20% global-reserve range for PERC and TOPCon, with SHJ alone remaining slightly above this threshold. By contrast, the High-demand pathway, which implies an average annual demand growth of about 8.3%, remains constrained under every combination in Table 8, as even the strongest case records BLOR values above 100%. This indicates that demand moderation is a critical precondition for physical feasibility rather than merely a policy option.

The results therefore show a clear trade-off. Increasing ISS deployment reduces land requirement for CGM, while silver-thrifting reduces material pressure. The technology-adjusted land columns further show that TOPCon and SHJ can reduce land pressure relative to PERC, but this comes alongside higher silver requirements. Thus, as solar deployment becomes larger, especially under the High-demand pathway, reducing one constraint does not automatically remove the other.

Taken together, these results identify a distinct land-mineral paradox within India's solar-dominant pathway. While the broader literature recognises cross-resource trade-offs, the case identified here is India-specific and threshold-based [71]. It shows that higher-efficiency PV technologies provide limited relief to CGM land pressure, but can increase silver demand to the point where silver becomes a binding feasibility constraint.

The novelty therefore lies not in restating resource trade-offs, but in quantifying where this trade-off becomes critical under India-specific demand pathways, CGM-ISS land-accounting cases and technology-specific silver intensities. Technological improvement therefore does not remove the physical constraint, but shifts part of the pressure from land availability to mineral dependence. India's solar feasibility therefore requires demand moderation, material-intensity reduction and further expansion of ISS deployment.

Table 8: Integrated Policy-Sensitivity Outcomes for Land and Silver Constraints in 2070

Demand scenario	Policy case: mix and silver-intensity reduction	Solar capacity (GW)	PERC				TOPCon				SHJ			
			Area (km ²)	BLOR (%)	Silver (tonnes)	Reserve share (%)	Area (km ²)	BLOR (%)	Silver (tonnes)	Reserve share (%)	Area (km ²)	BLOR (%)	Silver (tonnes)	Reserve share (%)
Low	80:20, no silver reduction	1,250	20,500	12	19,000	3	19,500	11	32,000	5	18,500	11	43,000	7
Low	70:30, 25% silver reduction	1,250	18,000	10	14,500	2	17,000	10	24,000	4	16,500	10	32,000	5
Low	60:40, 50% silver reduction	1,250	15,000	9	9,500	2	14,500	8	16,000	3	14,000	8	21,000	3
Base	80:20, no silver reduction	7,500	120,500	70	115,000	19	114,000	66	190,000	31	110,500	64	252,000	41
Base	70:30, 25% silver reduction	7,500	105,500	61	86,000	14	100,000	58	143,000	23	97,000	57	189,000	31
Base	60:40, 50% silver reduction	7,500	90,500	53	57,000	9	85,500	50	95,000	16	83,000	48	126,000	21
High	80:20, no silver reduction	15,500	251,500	147	239,000	39	238,500	139	398,000	65	231,000	135	527,000	86
High	70:30, 25% silver reduction	15,500	220,000	128	180,000	30	208,500	121	298,000	49	202,500	118	395,000	65
High	60:40, 50% silver reduction	15,500	188,500	110	120,000	20	179,000	104	199,000	33	173,500	101	263,000	43

Note. Deployment ratios refer to CGM:ISS solar. Only CGM solar is counted in the BLOR calculation. ISS solar is treated as outside the barren-land denominator rather than as land-neutral. Silver-intensity reductions are applied separately to PERC, TOPCon and SHJ.

5. Conclusion

This study examines whether India's 2070 net-zero pathway is physically feasible by connecting long-run electricity-demand forecasts with the solar capacity, land area and silver requirements needed to support a solar-dominant transition. Its core contribution lies in converting projected electricity demand into measurable physical constraints, rather than treating demand, land and minerals as separate planning issues.

The results confirm urbanisation as an important long-run driver of India's electricity demand, supporting its use as a key projection variable in the ARDL framework. Under the Base and High scenarios, the resulting demand paths translate into multi-terawatt solar capacity requirements by 2070. When these capacity needs are converted into land and silver requirements, the transition appears more constrained than conventional capacity-based assessments suggest. CGM solar places heavy pressure on barren and unculturable land, while silver demand becomes substantial even under conservative technology assumptions.

A key finding is the identification of a land-mineral paradox, understood as a cross-resource trade-off in which land-saving solar technologies can shift part of the physical constraint towards silver dependence. The integrated analysis shows that the Base pathway becomes more manageable when CGM dependence is reduced through ISS expansion and silver intensity declines sharply. However, no Base-demand combination fully resolves the silver constraint for SHJ within the 20% global-reserve threshold, and the High-demand pathway remains constrained under all policy combinations assessed. This makes demand moderation a necessary condition for feasibility rather than just an additional policy option.

Overall, the study adds a physical feasibility perspective to India's net-zero debate. Credible solar planning must move beyond installed-capacity targets and include efficient demand management, rooftop and building-integrated PV, floating solar, agrivoltaics, material-efficient technologies, diversified sourcing and long-term mineral-security strategies. Without such policy measures, a solar-dominant pathway may remain ambitious on paper but physically difficult to sustain in practice.

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