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Securing Regional Solar Supply Chains: Determinants and Preparedness of the Northeastern Region of India and ASEAN

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Abstract: *Renewable energy contributes to the acceleration of the energy transition, supports global environmental mitigation, and helps meet sustainable development goals. Energy connectivity of India's Northeastern Region (NER) with neighbouring countries particularly ASEAN assumes critical importance for accelerating economic integration. NER can play a three-dimensional role as power producer, exporter, and transit provider provided a quadrangular approach to build energy linkages and promote integration is consciously put in place. To understand whether the NER states are capable enough to take forward the solar supply chain development and bolster the ASEAN-India engagements in solar energy sector, this study has designed a state-level index of solar supply chain development by factoring in seven parameters, namely, (i) economic situations, (ii) environmental factors, (iii) spread of connectivity, (iv) financial enabling conditions, (v) mobility, (vi) human development, and (vi) social cohesion, which directly or indirectly influence the solar supply chain development in India. The results show that a clean and decent environment is must for development of solar supply chain. In addition, the study suggests that there is a need to improve the solar supply chain capability in the NER to enhance the economic growth. Leveraging policy support and reinvigorating existing institutions and creating new ones are imperatives for predicting the solar supply chain in the NER. This indexing may help track the trends, allowing for more informed decision-making in securing regional solar supply chain.*

Keywords: NER, India, ASEAN, Solar supply chain, Energy, Renewable energy

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1. Introduction

In support of the decarbonised economy by the middle of the century, many countries have identified potential pathways to more sustainable, reliable, and resilient energy supply chains. The development of renewable energy supply chains and regional connectivity also helps to achieve economic integration through increased trade and investments that reduce the costs of decarbonisation (Anbumozhi, 2019; 2023). Renewable energy, such as solar and wind, is primarily low-carbon and is capable of directly and effectively converting naturally available resources into electrical energy. However, a resilient and reliable renewable energy supply chain is diversified, both geographically and from a technology standpoint (De and Anbumozhi, 2023). Wind and solar power development and their efficiency in converting into electrical energy are influenced by different kinds of products and the materials used to produce them. In addition to efficiency, the availability of raw materials, manufacturing of components, and support of infrastructure are necessary conditions. In the case of solar power, initial material suppliers, solar module suppliers, and solar systems assemblers are all members of the solar supply chain (SSC). There are several steps in the manufacturing of crystalline polysilicon solar photovoltaic panels, the most popular technology to harness solar energy with a 95% market share (Kalmus et al., 2011; Kapoor et al., 2014). Raw materials, such as silicon, are procured by solar module manufacturers, who first make ingots and wafers by isolating refined polysilicon, and then combine them with other metals to produce cells. Solar module sellers sell modules to assemblers, who assemble them into devices and then sell them to customers.

To accelerate development and growth in the SSC, the government can help players cooperate with each other. Government tariffs (taxes or subsidies) not only increase the government's profit but members' profit also goes up. Government policies to develop solar energy technologies decrease the use of fossil fuels, and increase the use of domestic solar cell producers (Gopal, 2014; Gulia et al., 2022). The high installation of solar systems depends on government policy. Government subsidies lead to a reduction in solar system prices for end users. Furthermore, tariffs can induce the development of energy-saving technologies and sustainable objectives. Additionally, the government has an important effect on infrastructure provisions and skill development. Additionally, government taxes can augment the retail prices of foreign systems and persuade final customers to use domestic products (Xavier et al.,2019; Zhao et al., 2013). Foreign suppliers want to remain in the competitive market. For this reason, they intend to decrease the final price to overcome their competitors. On the other hand, taxes prevent foreign suppliers from exporting more foreign solar systems. The government's supportive policies can assist members in extending technologies for improving efficiency and developing the solar supply chain (IEA, 2022; Oliveira et al., 2019).

The main goal of this paper is to determine both the downstream and upstream determinants in securing the regional solar supply chain. It investigates the enabling conditions in the presence of government support at the national and regional levels.

The rest of the paper is arranged as follows: Association of Southeast Asian Nations (ASEAN)-India linkages in the energy sector with particular reference to the Northeastern Region (NER) of India are discussed in Section 2. Section 3 discusses the motivation for designing an Indian state-wise solar supply chain development index, followed by the data and methodology in Section 4. The models used for the supply chain development, as well as the scenario results at the state, national, and regional levels, are analysed in Section 5. The determinants of solar supply chain development and the policy implications are concluded in Section 6.

2. Renewable Energy and ASEAN-India Energy Relations

Renewable energy is considered an important component for reducing reliance on conventional sources of energy, supporting global environmental mitigation, accelerating energy transition, and meeting the Sustainable Development Goals (SDGs).[1] Renewable energy is a key element of both India's and ASEAN countries' energy planning. India has set an ambitious climate goal for 2030, and it even boosted its pledge during the 2021 Conference of the Parties (COP26). India's climate action aims to achieve a non-fossil energy capacity of 500 GW, meet 50% of its energy requirements from renewable energy, reduce the total projected carbon emissions by 1 billion tonnes by 2030, reduce the carbon intensity of its economy by less than 45%, and achieve the target of net zero by 2070 (PIB, 2022a).

The energy connectivity of India's NER with neighbouring countries, particularly ASEAN countries, assumes critical importance for accelerating economic integration. Enhancing collaboration in renewable energy would be mutually advantageous for regional cooperation as well as help ASEAN secure 23% of primary energy from renewable sources by 2025 under the ASEAN Plan of Action for Energy Cooperation (APAEC). With abundant natural and renewable resources, the NER holds a strategic position geographically and economically to support its neighbours, particularly ASEAN, in meeting their energy demand

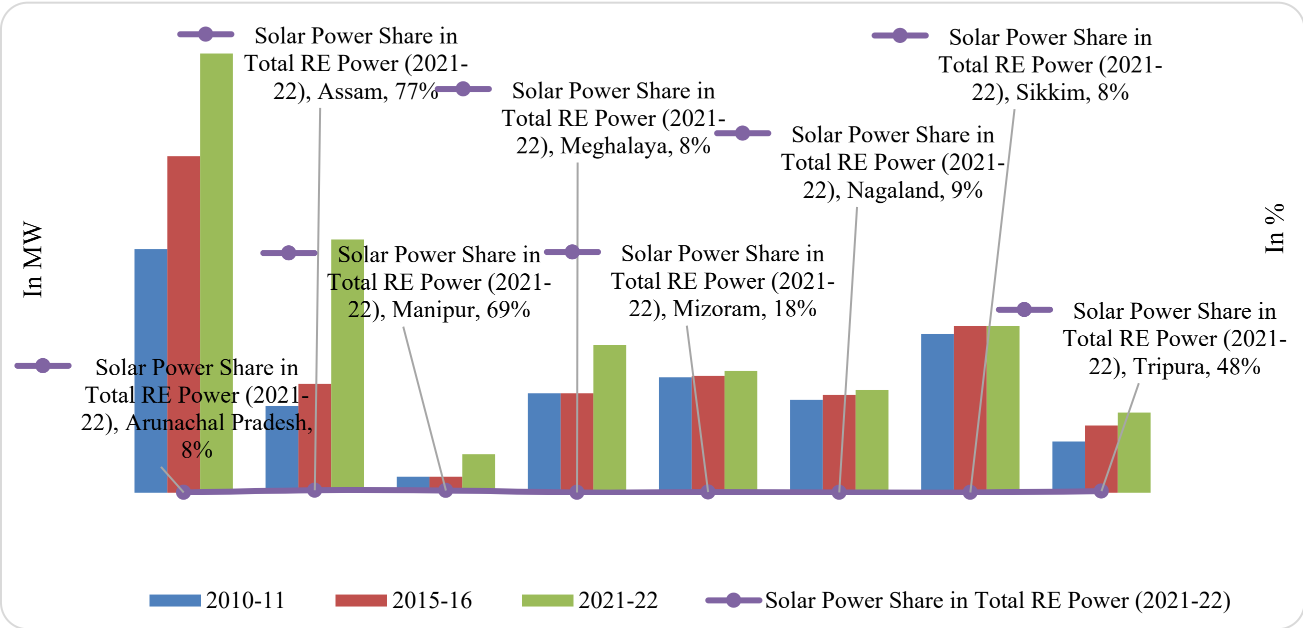
[1] SDG-7 i.e., increasing access to affordable, reliable, sustainable, and modern energy, can accelerate climate change mitigation through GHG emissions reduction.

and accelerating the clean energy transition. For India and the NER in particular, energy connectivity with ASEAN provides an opportunity for building resilient supply chains and predicating renewable energy trade.

India is home to a vast supply of renewable energy resources and ranks fourth in renewable energy capacity globally (PIB, 2022b). It is one of the top countries investing in renewable energy. The installed capacity of grid-interactive renewable power increased to 94,434 MW in 2021 from 18,394 MW in 2010 (RBI, 2022). Solar energy is considered the most abundant of all renewable resources in India, making it a low-cost destination for solar energy. The potential for solar power in terms of direct normal irradiance is very large. However, there is disparity in solar potential across states. India receives nearly 3,000 hours of sunshine every year, which is equivalent to 5,000 trillion kWh of energy, with most parts receiving 4–7 kWh per square metre per day (MNRE, 2022), whereas NER states receive average solar insulation in the range of 3–5 kWh per square metre per day for more than 300 sunshine days. Amongst the NER states, Arunachal Pradesh leads in the installed capacity of grid interactive renewable power, with only an 8% share of solar power in total renewable power in 2021 (Figure 1). At 77%, Assam had the highest solar power share in total renewable power in 2021, followed by Manipur (69%) and Tripura (48%).

Over the years, the solar energy sector in India has witnessed tremendous growth in grid-connected power generation capacity. It has been playing a vital role in addressing India's energy demand needs and ensuring energy security. Solar energy has taken a central place in the National Action Plan on Climate Change (NAPCC) with the National Solar Mission (NSM) as India’s Flagship Policy on renewable energy. The NSM was launched in January 2010 based on the vision to make India’s economic development energy efficient by setting up an enabling environment for solar technology penetration in India and making it a global leader in solar energy. The NSM seeks to increase solar power generation from photovoltaic (PV) and concentrated solar power (CSP) technologies to achieve retail grid parity by 2022 and parity with conventional (coal-based) power generation by 2030. The policy intends to install 100 GW of solar energy plants in three development phases: Phase I (2010–2013), Phase II (2013–2017), and Phase III (2017–2022).

Figure 1: Installed Capacity of Grid Interactive Renewable Power in NER States



Source: Calculated by authors based on the Ministry of Statistics and Programme Implementation (MoSPI) Database.

The NSM also seeks to establish a domestic solar manufacturing base to feed a growing domestic industry as well as global markets, hence becoming a major global solar player. Under this mission, the government introduced a Solar PV Manufacturing Scheme to build up the manufacturing capacity for solar PV modules, cells, wafers/ingots, and poly-silicon in India. Poly-silicon, ingots, wafers, solar cells, and solar modules are the required raw materials for manufacturing solar panels/modules (Figure 2). India had installed 6.6 GW of solar cells and 38 GW of solar modules until April 2023. Whilst the existing installed solar manufacturing capacity of the initial stages of the PV value chain, i.e. ingots and wafer manufacturing, is at a rudimentary stage, only one manufacturer (Adani Solar) has demonstrated the manufacturing of ingots and wafers.[2] Adani Solar has also initiated wafer production and plans to add 2 GW of ingot/wafer capacity by December 2023 and intends to scale up capacity to 10 GW by 2025. For wafer manufacturing, Emmvee Photovoltaic has announced setting up 1.5 GW of wafer-to-module capacity in India by the end of 2023 (Gulia et al., 2023). Manufacturing capacity for polysilicon has not yet begun in the country. Even though solar cell manufacturing capacity has increased in the last few years, it significantly lags behind module manufacturing capacity.

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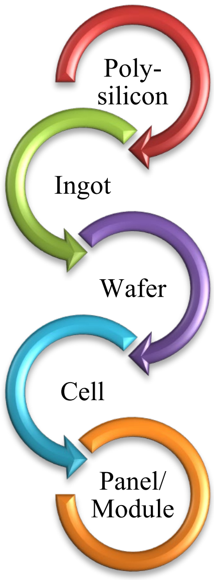
[2] Adani Solar introduced a large-sized monocrystalline silicon ingot at its Mundra (Gujarat) facility in December 2022. See https://www.livemint.com/industry/energy/adani-solar-introduces-india-s-first-large-sized-monocrystalline-silicon-ingot-11671630417696.html.

Given the limited manufacturing capacity available for cells, wafers/ingots, and polysilicon, India is heavily dependent on imports, mainly from China.

Figure 2: Solar PV Value Chain



Source: Authors.

Considering its ambitious solar energy targets, India has rolled out various policy measures and incentives to encourage solar power generation and enable the growth of the solar industry (see Box 1). The Ministry of New and Renewable Energy (MNRE) is the nodal agency for India for all matters relating to new and renewable energy. The MNRE aims to develop and deploy new and renewable energy to supplement the energy requirements of the country. India has also launched the production-linked incentive (PLI) scheme for the 'National Program on High-Efficiency Solar PV Modules', which aims to support solar developers in increasing the domestic manufacturing capacity of solar cells and modules and also integrate backwards in the supply chain towards poly-silicon, ingots, wafers, and solar cells by setting up vertically integrated solar manufacturing facilities. Tranche-I of the scheme envisaged setting up 10 GW of fully integrated solar PV module manufacturing capacity. In 2022, Tranche-II of the PLI Scheme for High-Efficiency Solar PV Modules was approved, which envisages the setting up of another about 65 GW per annum of fully/partially integrated solar PV module manufacturing capacity (PIB, 2023a). Tranche-II is expected to bolster the *Atamnirbhar Bharat* initiative and generate direct employment of about 1,95,000 and indirect employment of around 7,80,000 persons (PIB, 2023a).

Box 1: Policies to Promote Solar Energy in India

Policy	Description
Basic Custom Duties (BCD)	India imposes a 25% BCD on imported solar cells and 40% on solar modules to promote domestic manufacturing by making the domestic cells/modules competitive.
Domestic Content Requirement (DCR)	To develop the solar PV manufacturing industry, the Indian government has adopted schemes with a DCR, which provides a mandatory requirement for the manufacturer to use domestically manufactured modules. These schemes include the Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM) Scheme and the Central Public Sector Undertaking (CPSU) Scheme.
Solar PV Generation-based Incentive Scheme	The MNRE developed a strategy in January 2008 for incentives based on generation for both solar thermal and solar photovoltaic installations connected to the grid. The scheme has been extended to all current approved firms for state and central power production and to private and public power sector PV producers.
Generation Based Incentives (GBIs) for Solar	The installation of GBIs was less than 33 kW for limited solar grid projects. The goal of the GBIs is to bridge the gap between the basic tariff of Rs5.5 and the Central Electricity Regulatory Commission (CERC) as a financial opportunity.
Jawaharlal Nehru National Solar Mission (JNNSM), 2010	This is popularly known as the National Solar Mission, which is a part of India's National Climate Change Action Plan (NAPCC). In 2014, the Indian government overhauled the Solar Mission. It targets solar electricity power installed for 100 GW by 2022. The government has introduced a range of initiatives to boost renewable energy to meet this ambitious target.
Production-linked Incentive (PLI) Scheme	In April 2021, the Government of India's PLI Scheme on the National Program on High Efficiency Solar PV (Photovoltaic) Modules was launched. The scheme, with a financial outlay of Rs4,500 crore (US$616 million), was intended to support 10 GW of capacity of integrated solar PV manufacturing plants. The PLI scheme provides several direct and indirect benefits such as: direct investment of about Rs17,200 crore in solar PV manufacturing projects, demand of Rs17,500 crore over five years for the balance of materials, direct employment of about 1,95,000, indirect employment of around 7,80,000 persons, and import substitution of about Rs17,500 crore every year.

Source: MNRE (2021) and Saxena et al. (2020).

The Government of India has introduced several schemes to promote the development of solar energy in the country (see Box 2). The Solar Energy Corporation of India (SECI), under the administrative control of the MNRE, is the nodal body for implementing the national renewable energy-related schemes and has issued tenders for 10,000 MW of hybrid/Round the Clock (RTC) peak power capacity, of which 5,350 MW has already been awarded.[3]

Box 2: Ongoing Schemes

Ongoing Schemes	Description
Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan (PM KUSUM)	PM-KUSUM scheme is one of the largest initiatives in the world to provide clean energy to more than 3.5 million farmers by solarising their agriculture pumps.
Roof Top Solar (RTS) Programme	In 2015, Phase I of the RTS programme was launched in which incentives and subsidies were provided for residential, institutional, and social sectors. Achievement-linked incentives were also provided for the government sector. In 2019, Phase II of the programme was launched with a target of achieving cumulative capacity of 40,000 MW by the year 2022.
Solar Parks	The scheme for the development of solar parks has a target capacity of 40 GW. All states and union territories are eligible for receiving benefits under the scheme. Solar parks are being developed by agencies of the central/state governments, joint ventures between agencies of the aentral and the state governments, and also by private entrepreneurs.
Green Energy Corridors	The Inter-State Transmission System (ISTS) component consisting of 3,200 km transmission lines and 17,000 MVA substations was completed in March 2020. The ISTS component has been sanctioned to the eight RE rich states of Tamil Nadu, Rajasthan, Karnataka, Andhra Pradesh, Maharashtra, Gujarat, Himachal Pradesh, and Madhya Pradesh for over 20,000 MW of renewable power.
Greening of Islands	The government intends to fully convert the Andaman and Nicobar, and Lakshadweep islands to green energy, where energy needs will be met using RE sources. The Greening of Islands programme aims to deploy 52 MW of distributed grid-connected solar PV power projects.
Solar Cities	At least one city (either the state capital city or a well-known tourist destination) in each of the states of India is being developed as a solar city. All electricity needs of the city will be fully met from RE sources, primarily from solar energy.
Waiver of Inter State Transmission System Charges	The Inter State Transmission System charges and losses for inter-state sale of power from solar and wind power projects have been waived for all projects to be commissioned up to 30 June 2023.

Source: MNRE (2021).

[3] See https://pib.gov.in/PressReleseDetailm.aspx?PRID=1776512; ISA (2020), https://isolaralliance.org/images/flag%20pdf/India.pdf.

The NER states have been given special attention for developing and deploying grid and off-grid solar energy systems through various schemes. Under the Solar Parks Scheme, six solar parks have been approved with an aggregate capacity of 290 MW in the NER states. Three solar parks are currently under implementation in Manipur (Manipur Tribal Development Corporation Ltd. (MTDCL)), Meghalaya (Meghalaya Power Generation Corporation Ltd. (MePGCL)), and Mizoram (Power & Electricity Department), and another three solar parks with an aggregate capacity of 230 MW were cancelled due to slow progress (MNRE, 2023). Under the Grid-connected Rooftop Solar Programme, aggregate capacity of 82.3 MW has been allocated to Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura under Phase II of the programme (MNRE, 2023). Solar off-grid programmes, such as the Off-grid and Decentralized Solar PV Applications Scheme, Atal Jyoti Yojana (AJAY), and PM-KUSUM Scheme are also being implemented in the NER states. Grid-connected solar power plants up to 2 MW, standalone solar pumps, and the solarisation of existing agricultural pumps are being supported under the PM-KUSUM Scheme (MNRE, 2023).

Besides this, several Indian states have also actively participated in promoting solar energy technologies by providing additional or alternative incentives for solar developers (Kapoor et al., 2014). NER states have been proactively implementing several policies to harness solar power to meet the increasing electricity demands whilst promoting green and clean energy sources.

In 2015, the Assam Electricity Regulatory Commission (AERC) adopted the Grid Interactive Solar Energy Systems Regulation, with the aim of fulfilling the electricity requirement of household, commercial, and industrial consumers by setting up small solar plants under the NSM and feeding the surplus power into the grid (AERC, 2015). The Assam Solar Energy Policy was adopted by the Government of Assam with the objective of accelerating the participation of developers and investors in expanding states' solar power capacity and encouraging residential, commercial, industrial, and government consumers to adopt on-grid (solar power and rooftop solar power plant) and off-grid solar applications.

The Arunachal Pradesh State Electricity Regulatory Commission (APSERC) implemented the Regulation on Rooftop Solar Grid Interactive Systems based on net metering[4] in 2016 for the promotion of grid-connected solar rooftop photovoltaic systems (APSERC,

[4] Under the net metering arrangement, the energy generated from solar PV systems installed at the premises of a user is consumed by the consumer, and surplus electricity, if any, is delivered to the distribution utility after off-setting the electricity supplied by the distribution utility during the applicable billing period.

2016). The policy provides several incentives in the form of exemptions from wheeling and transmission charges and electricity duty within the state.

The Manipur Government adopted the Manipur Grid Interactive Rooftop Solar PV Power Policy in 2014 to promote grid-quality solar power generation (Science and Technology Department, Government of Manipur, 2014). The scheme also supports Grid Connected Rooftop Solar Photovoltaic (GRPV) systems. Manipur Renewable Energy Development (MANIREDA), the implementing agency, provides solar installations owned by consumers and solar installations owned, operated, and maintained by third-party business models to users. The scheme also provides a net metering facility for the Manipur State Power Distribution Company Ltd. (MSPDCL) for consumers intending to encourage solar green energy and set up solar PV plants at available places on rooftops.

In 2015, the Meghalaya State Electricity Regulatory Commission adopted the Rooftop Solar Grid Interactive system based on net metering for promoting GRPV in Meghalaya. The scheme also provides a net metering facility for Meghalaya Power Generation Corporation Limited (MePGCL) consumers for setting up solar PV plants. The government also has a Meghalaya Rooftop Portal for processing solar rooftop PV applications for accelerating the deployment of GRPV installations in the state of Meghalaya. The web portal serves as an integrated platform for multiple solar rooftop stakeholders, namely, Meghalaya Power Distribution Corporation Limited (MePDCL), and empanelled vendors and consumers.[5]

The Government of Mizoram adopted the Mizoram Solar Power Policy (2015) to create an enabling environment for prospective solar power developers to harness solar power in the best possible manner and also to ensure a sustainable fuel mix in the long run (Power & Electricity Department, Government of Mizoram, 2015). The policy is applicable for all solar energy-based grid and off-grid power projects (solar PV/solar thermal) in the state of Mizoram. Zoram Energy Development Agency (ZEDA) is the nodal agency that implements the solar power projects under the policy. The policy provides several incentives for solar project developers, including waiving of the electricity duty for new manufacturing facilities and ancillaries of the solar power projects, exemption from demand cut and entry tax/VAT, refunds of stamp duty, etc.

Nagaland Electricity Regulatory Commission (NERC) implemented the Regulation of Rooftop Solar Grid Interactive Systems based on net metering in 2016 for the promotion of GRPV in Nagaland. It provides several exemptions and incentives to users. In 2022, the

[5] For details, see https://meghsolar.meghalaya.gov.in/.

Nagaland Government signed an agreement with Halo Energie Pvt Ltd., for setting up a 20 MW solar power project near Jalukie, Nagaland (India Times, 2022).

In 2014, the Sikkim State Electricity Regulatory Commission introduced regulations for grid-interactive distributed solar energy systems in the state, providing several exemptions and relaxations for users. In 2019, Sikkim introduced the GRPV System Policy to promote GRPV deployment and increase the dependence on solar energy in the state (Power Department, Government of Sikkim, 2019). Sikkim Renewable Energy Development Agency (SREDA) is the nodal agency for devising various policies and schemes for developing GRPV systems. These policies include net metering, virtual metering, gross metering facilities for users, capital expenditure, utility-driven business models, exemption from the electricity duty and cess, conversion charges, wheeling charges and open access charges, provided budgetary support, generation-based incentives (GBI), and private investment, as well as the creation of green funds.

The Tripura Energy Vision 2030 Road Map envisions producing around 500 MW of solar energy by 2030.[6] The Tripura Renewable Energy Development Agency (TREDA), under the aegis of the MNRE, has devised various policies and schemes for the development of solar power in the state for residential, commercial, and industrial users. TREDA provides net metering policies to residential, commercial, and industrial users. TREDA also provides flexibility in choosing the business model. For example, the CAPEX business model is available for self-owned solar system users, and the RESCO model (tariff applicable as per regulations set by the system owner) is available for users who want solar systems owned by a third party. Perks such as no wheeling, banking, and cross-subsidies are available for solar users in Tripura. Solar project users can also avail of financial aid, such as a 10-year tax holiday and 40% accelerated depreciation, and loans of up to Rs15 crore can be availed of by industrial users for developing solar projects under priority sector lending.

However, the central and state governments' lack of consistent renewable energy policies has hampered the expansion of the solar energy market in India. Moreover, frequent fluctuations in central and state government policies have stalled the growth of solar power deployment, particularly in the rooftop solar power plant segment. Although the solar industry is at the forefront of renewable energy, it constantly faces policy impediments. Another problem facing the solar industry is the lack of clarity surrounding Goods and Services Tax

[6] For details, see https://www.constructionworld.in/energy-infrastructure/power-and-renewable-energy/tripura-unveils-ambitious-plan--500-mw-solar-power-by-2030/42793.

(GST) rates, as well as restrictions on favourable features like net metering and the banking of renewable energy (Gulia et al., 2023). Furthermore, India's heavy dependence on imports of solar cells and frequent fluctuations in the Basic Customs Duty (BCD) have been deterring the growth of the solar market in India. Therefore, pertinent stakeholder discussion is imperative for removing the policy barriers.

At present, India stands fourth in solar PV deployment across the globe (PIB, 2022b). Between 2011 and 2022, solar power installed capacity grew at a compound annual growth rate (CAGR) of 49.4%, from 0.5 GW in 2011 to 61.97 GW in 2022. This indicates that India missed its goal of having 100 GW of installed solar capacity by 2022. The 38 GW shortfall from the 2022 target can be attributed to multiple challenges, including regulatory roadblocks, high dependence on imports of downstream components, supply chain fluctuations, high capital and operating costs, a lack of skilled manpower, export limitations, a lack of research and development (R&D), the use of obsolete technology, net metering limits, basic customs duty (BCD) on imported cells and modules, issues with the approved list of models and manufacturers (ALMM), lack of financing infrastructure and banking restrictions, etc. (Gulia and Garg, 2022). In addition, the economic impact of the Covid-19 pandemic also acted as a constraint in solar capacity addition.

The Indian Solar PV manufacturers have been gearing up to increase the existing manufacturing capacities of cells and modules and build fully integrated PV manufacturing capacities in the coming years to meet their commitments in the larger renewable energy ecosystem. By 2026, module manufacturing is expected to show a threefold increase (110 GW) in India (Gulia et al., 2023). In addition, 52 GW of solar cell capacity is likely to be added by 2026 by domestic cell manufacturers (Gulia et al., 2023). Wafer/ingot manufacturing is expected to be around 56 GW by 2026 (Gulia et al., 2023). Given the complex and capital- and energy-intensive manufacturing process of polysilicon, only manufacturers with large capital reserves are likely to be at the forefront of domestic polysilicon manufacturing. With the setting up of integrated manufacturing systems by PLI Scheme beneficiaries, we can expect the establishment of 38 GW of polysilicon manufacturing capacities in the coming years.

After China, ASEAN countries have secured solar PV component manufacturing capacity for wafers, cells, and modules. However, the manufacturing of solar PV components is very limited and concentrated in a few countries, such as Malaysia, Viet Nam and the Republic of Korea (Gulia et al., 2023). Even though the photovoltaic and solar thermal equipment market is growing and thriving in ASEAN countries, they still have to contend with global competitors who have excess capacity, lower prices, and higher incentives.

On the international front, India launched the International Solar Alliance (ISA) at COP 21 in 2015 and amended the framework agreement in 2020 with the objective of increasing the deployment of solar energy technologies as a means for bringing energy access, ensuring energy security, and driving energy transition in its member countries.[7] About 110 countries are signatories to the ISA Framework Agreement, of which 90 countries have submitted the necessary instruments of ratification to become full members of the ISA. The ISA targets US$ 1 trillion of investment in solar by 2030, which would be significant in bringing the world closer to the energy transitions needed. To further boost energy connectivity, India and the United Kingdom jointly launched a 'green grid' initiative named the 'One Sun, One World, One Grid' initiative at COP 26, which aims to connect inter-regional energy grids to transfer solar energy across borders, leveraging the differences of time zones, seasons, resources, and prices between countries and regions (PIB, 2021).

Although India has made significant progress in expanding domestic module manufacturing capacity in the last decade, there has been prolonged dependence on upstream solar PV supply chain component imports (poly-silicon, ingots, wafers, and solar cells). The solar PV upstream and downstream components (solar panels/modules) manufacturing sector has lagged, which highlights the need for a vertically integrated domestic solar manufacturing ecosystem. On the other hand, ASEAN countries have been showing continuous growth in the solar PV components manufacturing sector. Therefore, developing collaborative and cooperative mechanisms between India's NER and ASEAN will create unique opportunities for securing the regional solar supply chain. With a significant increase in economic growth and rising demand in the NER and Southeast Asian region, building strong regional supply chains and/or production networks for solar energy will have an important role to play in meeting regional energy security in the coming years. Forging close ties in the energy sector will also help in establishing sustainable, vertically integrated solar supply chain production networks and achieving the renewables target of 500 GW (300 GW of solar) by 2030.

[7] For details, see https://www.isolaralliance.org/about/background.

2.1. Prospects for NER-ASEAN Energy Cooperation

India and several of ASEAN's member states face common sustainable developmental challenges, as well as offer similar commitments in the Paris Climate Agreement that aim to maximise the use of clean energy sources. Therefore, ASEAN and India have called for deeper cooperation in the energy sector in general, and trade in renewable energy in particular, for attaining the Nationally Determined Contribution (NDC) targets and accomplishing Goal 7 of the Sustainable Development Goals (SDGs) of affordable and clean energy.

Renewable energy has been a key focus area of ASEAN-India energy cooperation since the adoption of the 'New Delhi Declaration on ASEAN-India Cooperation in Renewable Energy' in 2012. In January 2018, the leaders of ASEAN countries and India issued the Delhi Declaration to mark the 25th Anniversary of the ASEAN-India Partnership. They recommended: 'Continue to enhance cooperation for ensuring long-term food and energy security in our region through strengthening cooperation in agriculture and energy sectors; work together to promote the development of renewable energy technology through international platforms including the International Solar Alliance (ISA) where applicable.'[8] In 2021, the India Smart Grid Forum (ISGF) and ASEAN Centre for Energy (ACE) executed a memorandum of understanding (MoU) to establish a cooperation framework for initiatives in the areas of smart grids, electric mobility, and renewable energy development.

In 2022, India and ASEAN celebrated their 30th anniversary and ASEAN-India relations were upgraded to a comprehensive strategic partnership, where energy cooperation between them gained high priority. India has been supporting various initiatives, such as climate change, energy efficiency, clean technologies, and renewable energy under the ASEAN-India Green Fund. India has engaged in energy infrastructure development in the ASEAN region, such as building hydropower projects, power transmission lines, substations, and oil and gas pipelines, etc., but this has been limited to the CLMV countries (De and Kumarasamy, 2020). India already has bilateral power exchange interconnections with Nepal, Bhutan, and Bangladesh. On the other hand, ASEAN is developing two region-wide grids, including the ASEAN Power Grid and the Trans-ASEAN Gas Pipeline. The NER of India can be connected with the two grids via the power grid and gas pipelines through Myanmar. The India-Bangladesh electricity grid can further be linked to Myanmar, allowing energy access from not only Bangladesh and Myanmar but also ASEAN countries like Indonesia and Malaysia (De, 2013).

[8] For details see, https://asean.org/wp-content/uploads/2018/01/Delhi-Declaration_Adopted-25-Jan-2018.pdf

Forging ties in the energy sector assumes critical importance in the NER's integration with ASEAN. With improved infrastructure connectivity, increasing economic growth, increasing demand, and cost reductions, the development of sustainable energy solutions is imperative for enhancing cross-border energy trade. Amongst the various energy sources, solar energy can be considered a preferred option since the region is endowed with the highest band of average annual solar energy globally. Amongst the NER states, Assam, Manipur, and Mizoram have rich solar potential. Therefore, developing production networks is a key factor for the expansion of an effective, low-cost manufacturing base for the solar industry at the regional level.

Since the amendment of the ISA framework agreement, only two ASEAN countries, Cambodia and Myanmar, have signed and ratified the framework agreement. More ASEAN countries participating in the ISA framework agreement will help to build a global grid capable of transmitting renewable energy from anywhere, at any time, whilst also reducing carbon emissions and energy prices.

ASEAN and India may collaborate more in joint research studies, especially in grid stability and green management. There are immense opportunities from public-private partnerships for helping ASEAN and India to further accelerate their energy transition efforts. Therefore, there is vast potential for deepening cooperation and helping each other in moving towards low-carbon growth whilst dealing with the common challenges together.

Developing the regional solar supply chain with ASEAN can benefit India in terms of reducing dependency on foreign manufacturers, making domestic manufacturers competitive with international manufacturers, and creating domestic technology self-sufficiency and high-efficiency solar PV equipment, as well as transforming India from a net importer to a net exporter and making it a competitive and global player in solar PV manufacturing. Developing the solar supply chain between ASEAN and the NER of India in particular will provide new business opportunities for manufacturers in the NER to enter the upstream and downstream manufacturing markets as well as enhance knowledge sharing and the diffusion of technology. Given the proximity of NER states to Southeast Asia, developing the solar supply chain will provide easy access to credit and increase the pool of investors in the region. The creation of a strong and secure supply chain in India for the solar sector will enable the creation of jobs, reduce foreign exchange outflows, and lead to an increase in investments and sustainable growth of the sector in the long run (FICCI, 2016).

Therefore, this study aims to assess the Indian state-wise solar supply chain development based on an index over the period 2010–2021. An index helps us make better decisions whilst promoting green energy in India's northeast and its linkages with neighbouring ASEAN.

The outcome of this study will provide implications for solar energy trade supply chain linkages between the NER and ASEAN. As the green energy demand grows across borders, improving solar energy connectivity is crucial for building greater economic integration between ASEAN and the NER.

3. Motivation of the Study

India aims to reach net-zero emissions by 2070, with a commitment to meeting 50% of its gross electricity requirements from renewable energy sources by 2030.[9] India has achieved its commitment made at COP21 by already meeting 40% of its power capacity from non-fossil fuels – almost nine years ahead of its commitment where the shares of solar and wind in India's energy mix have grown rapidly.

Transition to a green economy is a statutory obligation. In the pathway to net-zero emissions by 2070, it appears that low-carbon energy sources are the major instruments. India has announced more ambitious targets for 2030, including installing 500 GW of renewable energy capacity, 50% of energy demand to be met by RE, reducing the emissions intensity of its economy by 45%, and reducing a billion tonnes of CO_2. Renewable energy is growing at a faster rate in India than any other major component of the economy.

Whilst moving towards net zero, India faces a number of pressing challenges. One of these challenges is to engage Northeast India in the journey to net zero. Northeast Indian states are very much vulnerable to natural disasters and climate change, however, they are yet to gain the needed capacity whilst transforming into a green economy. Engaging the states of India may make this transition more inclusive and rewarding.

Today, the NER's energy needs are primarily met by coal- and gas-based thermal power, whereas the region has high hydroelectric potential. Although the NER is better endowed with hydroelectricity, the region still lacks a reliable electricity supply. Over and above, there are financial constraints in undertaking large-scale renewable energy projects, such as solar PV.[10]

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[9] See https://climateactiontracker.org/countries/india/targets.

[10] For example, to reach net-zero emissions by 2070, the IEA estimates that US$160 billion per year is needed, on average, across India's energy economy between now and 2030.

It has been argued that the NER can play a three-dimensional role as a power producer, exporter, and transit provider provided a quadrangular approach to building energy linkages and promoting integration is consciously put in place. The prospect of energy trade between the NER and its immediate neighbours is, thus, very high, and the NER along with Bhutan and Nepal could become a subregional energy generation hub (Venkatachalam et al., 2019). However, progress, on the others has been limited due to bottlenecks and gaps in energy generation and transmission infrastructure, financial markets, and trade facilitation, as well as trade barriers and limited regional cooperation (Venkatachalam et al., 2019). The steady and sustainable energy infrastructure linkages can strengthen the NER's trade and economic engagements with the neighbouring countries (Brunner, 2010; De et al., 2020; Murayama et al., 2022).

A considerable volume of international investments, both in the fossil and renewable energy sectors, in ASEAN over the last 10 years has come from India, which has already been engaged in several small- and large-scale infrastructure developments in the region, particularly in Cambodia, the Lao PDR, Myanmar, and Viet Nam (many of which are driven by development aid). India has been building hydropower projects, power transmission lines and substations, and oil and gas pipelines in these countries. India has set up the International Solar Alliance (ISA) and has been guiding many developing countries and least developed countries (LDCs) in the energy transition. India has stopped subsidies for petrol and diesel and introduced subsidies for electric vehicles in 2019.

The transition to clean energy is a huge economic opportunity. Accelerating the shift to cleaner and more efficient technologies requires a reliable solar energy supply chain. The solar industry supply chain is primarily divided into two broad categories: PV and solar thermal. For example, solar PV is a crucial pillar of the clean energy transition worldwide, underpinning efforts to secure it through reliable supply chains. Today, China dominates global solar PV supply chains.[11] Although India and ASEAN's solar industries depend on imports of critical raw materials, there is still high scope for the development of domestic production based on some of the key inputs to secure and strengthen the supply chain between them and create direct and indirect employment opportunities, thereby deepening regional integration.

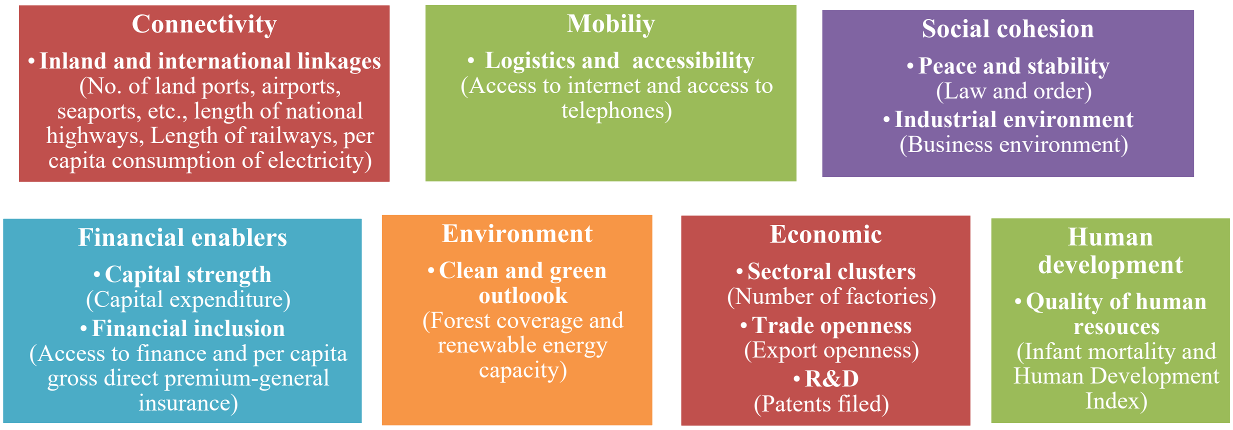
In order to understand whether the states are capable of taking forward the solar supply chain and whether they are endowed with the basic resources in order to strengthen ASEAN-

[11] Today, China's share in all the manufacturing stages of solar panels (such as polysilicon, ingots, wafers, cells, and modules) exceeds 80% (IEA, 2022).

India engagements in the solar energy sector, we have attempted to understand the inter-temporal positions of Indian states in the changing global order.

To design an index of solar supply chain development capability, we aim to factor in indicators to represent economic and supply chain components in the best possible manner. This indexing may help track the trends, allowing for more informed decision-making. The relative positions of Indian states in solar supply chain development are likely to change over time due to the enhancement of climate-adjusted initiatives. The index can show us the inter-temporal positions of NER states in comparison with other Indian states in solar supply chain development for the periods 2010 and 2021.

Figure 3: Framework of the Solar Supply Chain Development Index for Indian States



Source: Authors.

Illustrated in Figure 3, the framework of solar supply chain development covers seven major parameters of Indian states, covering mobility to connectivity to financial enablers to the environment. Whilst this is not an exhaustive list of parameters to capture the states' capability, we are driven by the availability of a common set of data that can better represent the solar supply chain development in the Indian context.

Connectivity in terms of air, road, rail, and electricity is the key catalyst for integrating Indian states' solar supply chain with ASEAN and further developing international production networks, leading to lower transaction costs and increased economies of scale (Brooks, 2010; Vidya and Taghizadeh-Hesary, 2021).

Mobility represents digital mobility in terms of access to and the use of information and communication technology (ICT), which affects the formation of social networks, new digital geographies, and its capability to provide access to networked societies and technologically smart mobility systems (Brandajs, 2021; Kalmus et al., 2011; Livingstone and Helsper, 2007;

Sheller and Urry, 2006; Larsen et al., 2006). Therefore, digital mobility would play a vital role in the development of the solar supply chain in states.

Social cohesion in terms of law and order and the business environment reflects an inclusive and sustainable society and the alignment of value chain logistics with institutions embedded in an economy's business environment. A cohesive society and business environment that moves in solidarity would lead to long-term progression and betterment of the social, economic, and business structures in an economy and would play an integral role in predicating organised regional solar supply chain and production networks (Gurzawska, 2020; Xavier et al., 2019; Schiefer and van der Noll, 2017; Helmsing and Vellema, 2011).

The strength of capital expenditure and financial inclusion are important financial enablers as they reflect higher productivity and the availability of well-developed capital markets, which can support businesses in accessing diverse sources of financial services in an affordable manner.[12] Access to finance, insurance, and capital spending can play a key role in developing the solar supply chain in an economy by boosting job creation and the skilling of human resources and reducing vulnerability to economic shocks (SEBI, 2020).

The environment and renewable energy have been gaining traction as an important area of focus worldwide. Renewable energy has become a part of economic sustainability calculations. A clean and green economy demands greater investment in renewables, which in addition to environmental benefits, could provide attractive dividends, such as job creation, economic growth, and energy security, etc.

The economic condition of the states describes the potential of the states and their economic structure in terms of business, industry, and trade orientation, which would help in developing a solar supply chain manufacturing base as well as trade opportunities (Constantine, 2017).

Human development in terms of the standard of living and infant mortality rate reflects an economy's quality of health and education, as well as access to resources and infrastructure. Increased demand for quality products and services may encourage supply chain integration through innovation, knowledge-sharing, and technological diffusion, which can further lead to the development of new supply chains (Santa et al., 2022; Huo et al., 2016).

Similarly, India and the ASEAN Member States' framework of solar supply chain development covers six major parameters for the country-level analysis (see Appendix Figure

[12] See World Bank (2022), https://www.worldbank.org/en/topic/financialinclusion/overview.

1). The parameters for the solar supply chain development index framework are discussed in detail in Section 4.2, Appendix Table 1, and Appendix Table 2.

4. Methodology and Data

We take the help of Principal Component Analysis (PCA) to derive a composite index of solar supply chain development across Indian states for the three cross-section years, namely, 2010-11, 2015-16, and 2021-22 following the guidelines as outlined in the *OECD Handbook to Construct a Composite Index* (OECD, 2008) (see Box 3).[13] Some studies have used a composite index for the developing supply chain, however, the literature is sparse.[14]

Box 3: Constructing a Composite Index

Methodological issues need to be addressed transparently prior to the construction and use of composite indicators in order to avoid data manipulation and misrepresentation. In particular, to guide constructors and users by highlighting the technical problems and common pitfalls to be avoided, the first part of the *OECD Handbook* discusses the following steps in the construction of composite indicators:

- Theoretical framework: A theoretical framework should be developed to provide the basis for the selection and combination of single indicators into a meaningful composite indicator under a fitness-for-purpose principle.
- Data selection: Indicators should be selected on the basis of their analytical soundness, measurability, country coverage, relevance to the phenomenon being measured and relationship to each other. The use of proxy variables should be considered when data are scarce.
- Imputation of missing data: Consideration should be given to different approaches for imputing missing values. Extreme values should be examined as they can become unintended benchmarks.
- Multivariate analysis: An exploratory analysis should investigate the overall structure of the indicators, assess the suitability of the data set and explain the methodological choices, e.g. weighting and aggregation.
- Normalisation: Indicators should be normalised to render them comparable. Attention needs to be paid to extreme values as they may influence subsequent steps in the process of building a composite indicator. Skewed data should also be identified and accounted for.
- Weighting and aggregation: Indicators should be aggregated and weighted according to the underlying theoretical framework. Correlation and compensability issues amongst indicators need to be considered and either corrected for or treated as features of the phenomenon that need to be retained in the analysis. Robustness and sensitivity. Analysis should be undertaken to assess the robustness of the composite indicator in terms of, e.g.

[13] India, a union of states, has 28 states and 8 union territories (UTs). For the sake of this analysis, we consider both Delhi and Jammu & Kashmir in the list of states in this study; both are, otherwise, UTs.
[14] For example, Oliveira et al. (2019), Shen and Loong (2018), Azevedo et al. (2013), Azevedo et al. (2011), and Gopal and Thakkar (2014).

the mechanism for including or excluding single indicators, the normalisation scheme, the imputation of missing data, the choice of weights, and the aggregation method.

- Back to the real data: Composite indicators should be transparent and fit to be decomposed into their underlying indicators or values.
- Links to other variables: Attempts should be made to correlate the composite indicator with other published indicators, as well as to identify linkages through regressions.
- Presentation and visualisation: Composite indicators can be visualised or presented in a number of different ways, which can influence their interpretation.

Source: OECD (2008).

4.1. Construction of the Composite Index

PCA is one of the unsupervised data mining tools used to reduce dimensionality in multivariate data and to develop composite scores. In PCA, the dimensionality of multivariate data is reduced by transforming the correlated variables into linearly transformed uncorrelated variables. PCA summarises the variation in a correlated multi-attribute to a set of uncorrelated components, each of which is a particular linear combination of the original variables. The extracted uncorrelated components are called principal components (PC) and are estimated from the eigenvectors of the covariance or correlation matrix of the original variables. Therefore, the objective of PCA is to achieve parsimony and reduce dimensionality by extracting the smallest number of components that account for most of the variation in the original multivariate data and to summarise the data with little loss of information.

Here, a composite index of the solar supply chain has been constructed using PCA on the unit-free indicators. PCA is sensitive to the units of measurement of the variables. Therefore, we make every variable unit free. After computing the unit-free values for the variables, we assign suitable weights to them and construct the composite solar supply chain development index (SSCDI). We assume that the SSCDI can be expressed as a linear function as follows:

$$\mathrm{SSCDI}_j^t = \sum_{i=1}^{n} \beta_i \times Y_{ij}^{t} \qquad (1)$$

where Y_i stands for indicator i for state j in time t. Here, the weights (β_i) are calculated based on the PCA's factor loadings. In other words, the weights are unrotated factor loadings derived from the PCA. The PCA displays the eigenvalues and eigenvectors from the PCA eigen decomposition. The eigenvectors are returned in orthonormal form, that is, uncorrelated and normalised. There are several advantages of PCA. The first and foremost advantage of PCA is that we avoid assigning arbitrary weights to the indicators and, instead, use the weights derived through PCA.

4.2. Data

Measuring the state-wise solar supply chain development index is a complex task. The main constraint is the choice of indicators and availability of data. However, the index of this paper reveals the gaps across Indian states and ASEAN member states and identifies the potential problems and areas for improvement. This study seeks to offer a practical approach to solar supply chain development and to assess the NER state-wise capacity whilst engaging with ASEAN in the energy sector.

In this study, we have selected a total of 18 indicators, spread over seven major variables across 30 states of India (see Table 1). Appendix Table 2 presents a detailed outline of the dataset and corresponding sources.

We consider seven broad variables which directly and indirectly influence the solar supply chain development in Indian states, and these are grouped as variables to represent (i) economic attributes, (ii) environmental factors, (iii) the spread of connectivity, (iv) financial enabling conditions, (v) mobility, (vi) human development, and (vi) social cohesion. The disclaimer is that this list is indicative only and non-exhaustive.

Similarly, we have selected a total of 13 indicators, spread over six major variables across India and ASEAN Member States (see Table 2). Given the availability of data, the six broad variables, which directly and indirectly influence the solar supply chain development in India and ASEAN, are grouped as variables to represent (i) economic attributes, (ii) environmental factors, (iii) the spread of connectivity, (iv) financial enabling conditions, (v) mobility, and (vi) human development. Appendix Table 3 presents a detailed outline of the dataset and corresponding sources.

Table 1: Indicators of the SSCDI and States of India

Variable	Indicator	State
1. Economic (3)	1.1 Industrial base (ib)	1. Andhra Pradesh
	1.2 Trade orientation (to)	2. Arunachal Pradesh
	1.3 R&D (rd)	3. Assam
2. Environment (2)	2.1 Forest coverage (fc)	4. Bihar
	2.2 Renewable energy (re)	5. Chhattisgarh
3. Connectivity (4)	3.1 Access to ports (port)	6. Delhi
	3.2 Spread of highways (high)	7. Goa
	3.3 Spread of railways (rail)	8. Gujarat
	3.4 Electricity availability (ea)	9. Haryana
4. Financial enablers (3)	4.1 Capital strength (cs)	10. Himachal Pradesh
	4.2 Financial inclusion (fi)	11. Jammu & Kashmir
	4.3 Business credibility (bs)	12. Jharkhand
5. Mobility (2)	5.1 Digital prowess (dp)	13. Karnataka
	5.2 Access to telephone (tel)	14. Kerala
6. Human development (2)	6.1 Standard of living (sl)	15. Madhya Pradesh
	6.2 Mortality (mor)	16. Maharashtra
7. Social cohesion (2)	7.1 Law and order (lo)	17. Manipur
	7.2 Business environment (be)	18. Meghalaya
		19. Mizoram
		20. Nagaland
		21. Odisha
		22. Punjab
		23. Rajasthan
		24. Sikkim
		25. Tamil Nadu
		26. Telangana
		27. Tripura
		28. Uttar Pradesh
		29. Uttarakhand
		30. West Bengal

Note: The highlighted states are known as the NER states of India.
Source: Authors.

Table 2: Indicators of the SSCDI for India and ASEAN

Variable	Indicator	Country
1. Economic (2)	1.1 Trade openness (trade)	1. Brunei Darussalam 2. Cambodia 3. India 4. Indonesia 5. Lao People's Democratic Republic 6. Malaysia 7. Myanmar 8. Philippines 9. Singapore 10. Thailand 11. Viet Nam
	1.2 Patent applications (pat)	
2. Environment (1)	2.1 Renewable energy consumption (re)	
3. Connectivity (6)	3.1 Logistics performance index (logis)	
	3.2 Liner shipping connectivity index (ship)	
	3.3 Rail lines (rail)	
	3.4 Air transport (logis)	
	3.5 Container port traffic (cont)	
	3.6 Access to electricity (elec)	
4. Financial enablers (1)	4.1 Foreign direct investment (fdi)	
5. Mobility (2)	5.1 Access to internet (inter)	
	5.2 Mobile cellular subscriptions (mobile)	
6. Human development (1)	6.1 Human Development Index (hdi)	

5. Analysis and Results

5.1. Determinants of solar supply chain development in Indian states

The state-wise scores of the estimated composite index (SSCDI) and corresponding ranks are presented in Table 3. Figure 4 presents the pictorial overview of the states in the SSCDI. The following observations are worth noting.

First, India’s top three states in the SSCDI are Tamil Nadu, Goa, and Delhi in 2021, whereas the bottom three states are Chhattisgarh, Jharkhand, and Bihar.

Second, whilst the rankings in the SSCDI of some of the NER states, such as Arunachal Pradesh, Assam, Meghalaya, and Tripura, declined over the period 2010 and 2021, those for other NER states like Manipur, Mizoram, Nagaland, and Sikkim improved between the years 2010 and 2021. From the NER, Mizoram, Sikkim, and Nagaland are the only states that fall within the top 10 states of India in the SSCDI in 2021, whereas Sikkim consistently ranks in the top 10 since 2010 (Figure 5).

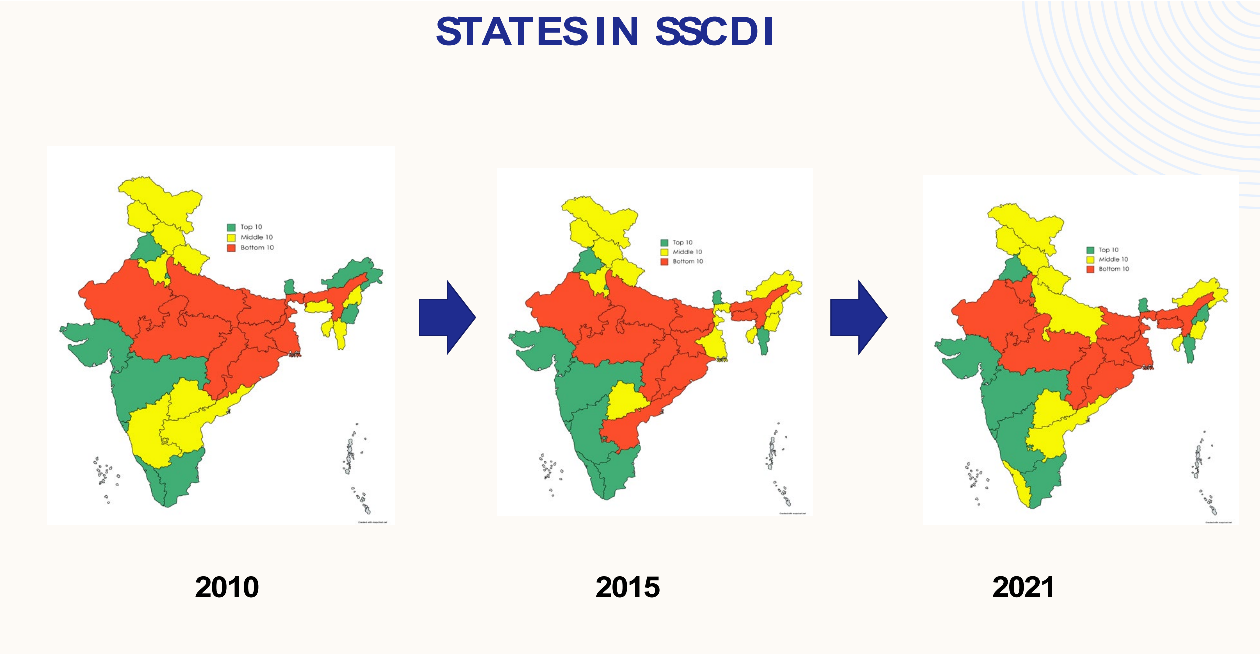
Table 3: States in the SSCDI

States	2010 Index	2010 Rank	2015 Index	2015 Rank	2021 Index	2021 Rank
Andhra Pradesh	4.31	17	3.74	21	3.52	20
Arunachal Pradesh	5.00	9	4.11	16	4.22	13
Assam	3.14	23	3.20	24	2.91	24
Bihar	2.51	29	2.46	30	2.22	30
Chhattisgarh	3.30	22	2.83	27	2.58	28
Delhi	8.00	2	7.00	3	5.64	3
Goa	9.08	1	7.45	2	5.78	2
Gujarat	5.23	7	6.20	5	5.45	6
Haryana	4.44	14	4.19	15	3.47	22
Himachal Pradesh	4.84	12	4.37	11	3.86	16
Jammu & Kashmir	4.38	15	3.88	17	3.93	14
Jharkhand	2.73	28	2.49	29	2.28	29
Karnataka	4.69	13	5.46	7	4.55	10
Kerala	5.33	6	5.21	8	4.29	12
Madhya Pradesh	2.98	26	2.71	28	2.61	27
Maharashtra	6.49	3	8.35	1	5.49	4
Manipur	5.36	5	4.32	12	4.35	11
Meghalaya	3.93	20	3.48	23	3.49	21
Mizoram	4.89	11	4.75	9	5.45	5
Nagaland	4.30	18	4.28	13	4.78	8
Odisha	3.09	24	3.00	26	2.88	25
Punjab	5.16	8	4.71	10	4.64	9
Rajasthan	2.99	25	3.06	25	2.77	26
Sikkim	4.90	10	5.68	6	4.94	7
Tamil Nadu	6.21	4	6.74	4	5.78	1
Telangana			3.78	20	3.86	15
Tripura	4.35	16	4.23	14	3.65	18
Uttar Pradesh	2.86	27	3.58	22	3.79	17
Uttarakhand	4.20	19	3.86	19	3.58	19
West Bengal	3.64	21	3.87	18	3.11	23
Rank correlation coefficient	0.931*** (for 2010-2015)			0.938*** (for 2015-2021)		

***Significant at the 1% level.

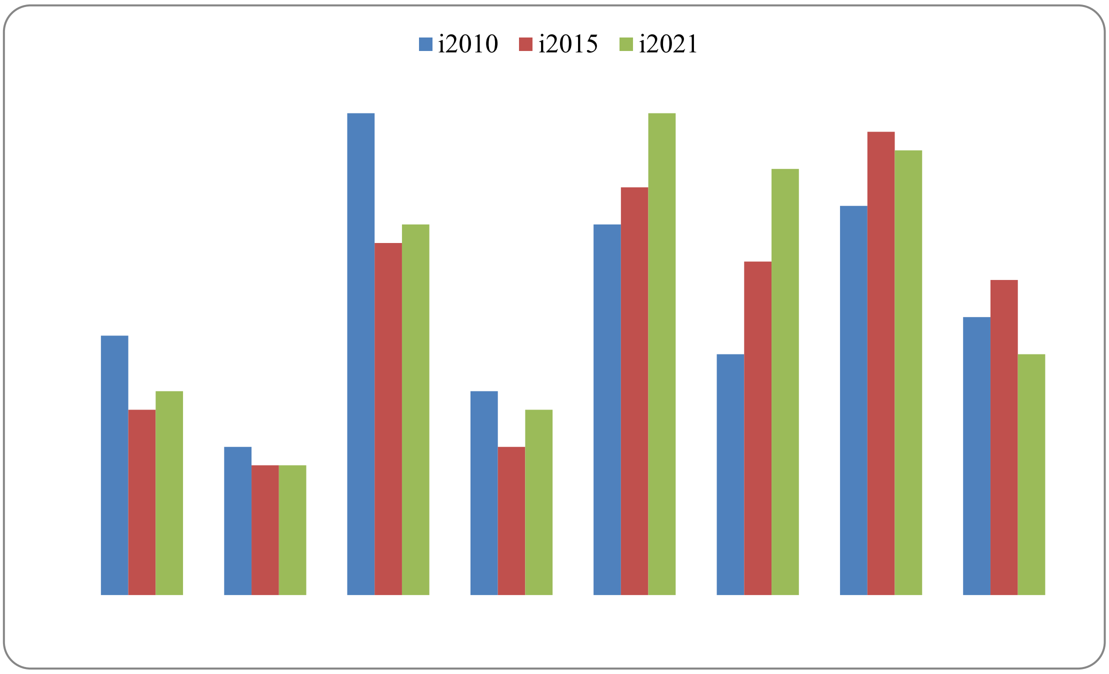
Source: Authors.

Figure 4: Indian States in the SSCDI over Time



Notes: The legends follow the top, middle, and bottom states in the SSCDI in Table 2. These are not true political maps of India and its states.
Source: Authors.

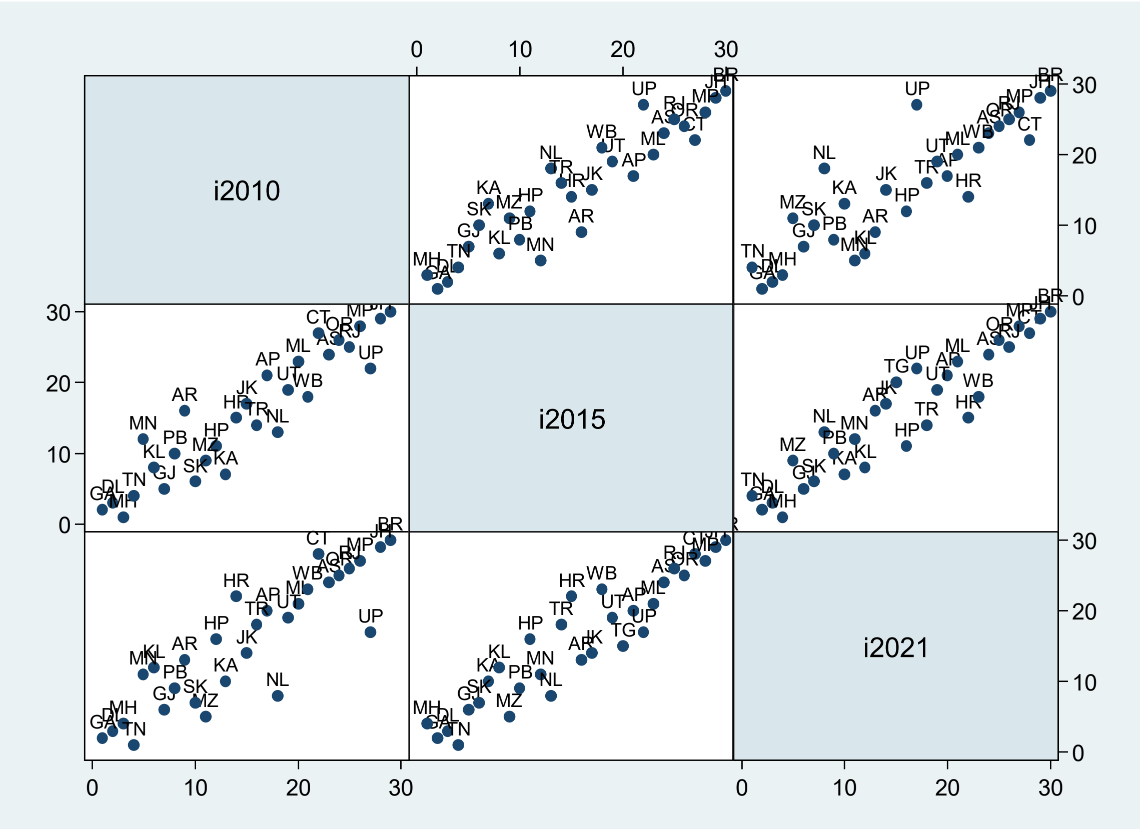
Figure 5: NER States in the SSCDI



Source: Authors.

Third, the Spearman's rank correlation coefficients clearly show that the Indian states' positions in the SSCDI do not change (0.931 for the period 2010–2015 vis-a-vis 0.938 for the period 2015–2021), thereby showing a high scale of rigidity between the states in the solar supply chain development in India. High and statistically significant correlation coefficients also show the strength and direction of the association of the states in the SSCDI between years. The positions of the states in the SSCDI between the years do not change, and this is well captured in the scatter diagrams in Figure 6.

Figure 6: Scatter Diagrams of the SSCDI



Source: Authors.

Fourth, the factor loadings (weights) of individual indicators in building the composite index were relatively balanced and changed over time (Table 4). Not a single indicator picked up most of the strength. The mix of weights over time clearly suggests the changing development structure of the states in the solar supply chain. In 2021, the top three important indicators in the SSCDI were the law and order situation, industrial base, and availability of electricity, whereas the same indicators were not in the same positions in 2010, according to the PCA. It appears that solar supply chain development is accompanied by peaceful and environmental strength as well as industrial base and electricity quality. A clean and decent environment is a must for the development of the solar supply chain, which is amply clear from the strengths of the weights of the individual indicators.

Table 4: Estimated Weights of the Individual SSCDI Indicators

Sr. No.	Indicator	2010		2015		2021	
		w	*r*	*w*	*r*	*w*	*r*
1	Capital strength (cs)	0.330	6	0.0387	18	0.189	13
2	Financial inclusion (fi)	0.354	3	0.2946	8	0.2574	8
3	Electricity availability (ea)	0.316	8	0.1666	14	0.0645	17
4	Renewable energy (re)	0.057	18	0.1613	15	0.1954	12
5	Spread of highways (high)	0.237	12	0.3195	4	0.2796	7
6	Spread of railways (rail)	0.184	13	0.2546	12	0.2409	10
7	Access to telephone (tel)	0.354	3	0.0746	16	0.0875	15
8	Mortality (mor)	0.265	11	0.3119	5	0.3313	3
9	Forest coverage (fc)	0.398	1	0.2571	11	0.3052	6
10	Industrial base (ib)	0.296	9	0.0737	17	0.0234	18
11	Access to ports (port)	0.081	17	0.2407	13	0.1351	14
12	Standard of living (sl)	0.328	7	0.3479	2	0.3125	5
13	Law and order (lo)	0.118	15	0.3826	1	0.3969	1
14	R&D (rd)	0.151	14	0.303	6	0.2488	9
15	Business environment (be)	0.340	5	0.2783	10	0.3167	4
16	Digital prowess (dp)	0.288	10	0.344	3	0.3383	2
17	Trade orientation (to)	0.098	16	0.2855	9	0.1974	11
18	Business credibility (bc)	0.378	2	0.2975	7	0.0758	16
Rank correlation coefficient	0.51*** (for 2010-2015)	0.78*** (for 2015-2021)			0.48*** (for 2010-2021)		

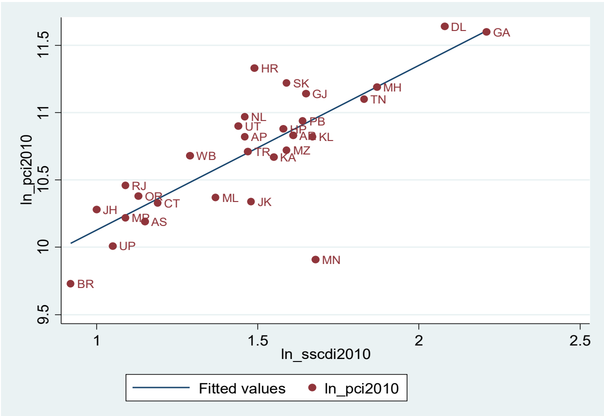
w = weight, r = rank.
Source: Authors.

Fifth, the SSCDI helps to assess the position of a state relative to others concerning the solar supply chain. Higher solar supply chain achievement should lead to higher income – that is, states with a high SSCDI would be expected to have high income per capita. Correlating the SSCDI with per capita income shows this link (Figure 7). Most states in Figure 10 are close to the trend line, and the fits are relatively robust in these cases.

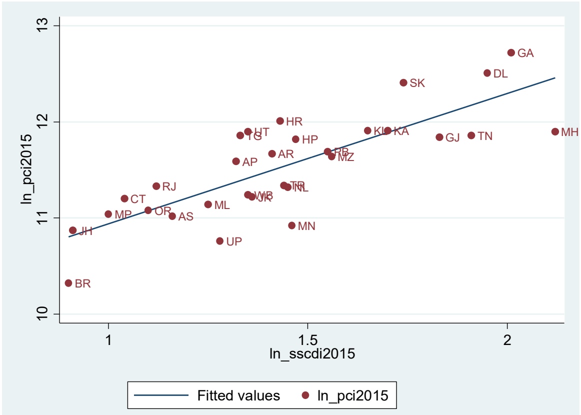
Sixth, an alternate index has been constructed for a robustness check (see Appendix 1 for the detailed methodology). The results of the alternative index scores and ranks follow the same direction as derived through the PCA. Spearman's correlations between the years reiterate the same as what we have assessed based on the PCA, indicating that our index is robust and statistically significant.

Figure 7: Link between SSCDI and Per Capita Income, 2010–2021

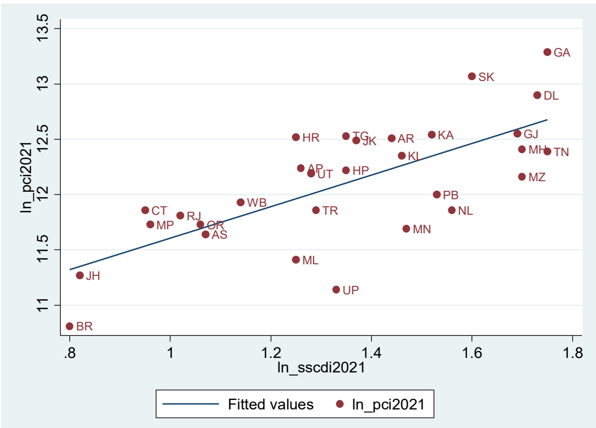
(a)



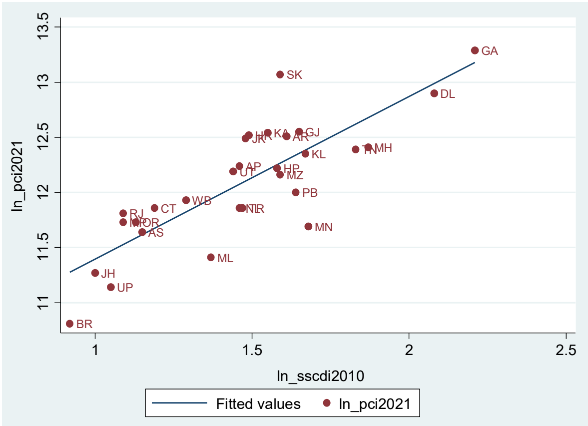
(b)



(c)



(d)



Source: Authors.

Seventh, solar supply chain development does influence a state's GDP. This is well captured in the estimated results presented in Table 5. We used the Least Square Dummy Variable (LSDV) model (or State Fixed Effects OLS model) to capture the impact of supply chain development on a state's GDP over the Panel Fixed Effects model (FEM), as the LSDV model captures the state effect and year effect by including a set of individual dummies for the state and year along with other explanatory variables that are otherwise excluded in the FEM model due to multicollinearity (as the state effect and year effect are already included in the FEM).[15]

[15] See Appendix 1 for the methodology.

Table 5: LSDV Model Estimates

	(1)	(2)	(3)	(4)	(5)	(6)
	ln_GSDP					
ln_SSCDI	18.954***	17.501***	0.292	1.789***	-0.076	-0.001
	(2.052)	(0.938)	(0.276)	(0.281)	(0.289)	(0.277)
Constant			27.546***		13.609***	25.875***
			(0.421)		(1.652)	(3.505)
ln_GSDP(t-1)				0.945***	0.560***	0.096
				(0.012)	(0.046)	(0.123)
Observations	89	89	89	60	60	60
R-squared	0.99	1.00	0.99	1.00	1.00	1.00
Akaike's IC				12.78	-75.40	-97.25
Bayesian IC				77.70	-8.38	-28.14
State Effect	Yes	Yes	Yes	Yes	Yes	Yes
Year Effect		Yes	Yes			Yes
NER States						
AR	-2.355	-4.108**	-3.608***	-0.398*	-1.553***	-3.208***
	(3.400)	(1.707)	(0.095)	(0.204)	(0.183)	(0.434)
AS	6.945***	4.669***	-1.026***	0.260*	-0.511***	-0.980***
	(2.479)	(1.265)	(0.106)	(0.147)	(0.156)	(0.181)
ML	1.649	-0.390	-3.273***	-0.176	-1.527***	-3.011***
	(2.864)	(1.424)	(0.102)	(0.212)	(0.201)	(0.414)
MN	-3.276	-4.956***	-3.595***	-0.331	-1.426***	-3.100***
	(3.604)	(1.795)	(0.152)	(0.233)	(0.177)	(0.438)
MZ	-5.155	-6.720***	-3.982***	-0.912*	-1.776***	-3.555***
	(3.392)	(2.166)	(0.170)	(0.509)	(0.232)	(0.476)
NL	-2.248	-3.996*	-3.438***	-0.742***	-1.652***	-3.197***
	(3.089)	(2.033)	(0.134)	(0.148)	(0.200)	(0.398)
SK	-5.424	-6.950***	-3.753***	-0.588***	-1.367***	-3.138***
	(3.505)	(1.933)	(0.223)	(0.212)	(0.163)	(0.449)
TR	0.015	-1.865	-2.856***	-0.314***	-1.295***	-2.600***
	(3.225)	(1.492)	(0.051)	(0.100)	(0.181)	(0.352)

Note: Standard errors are in parentheses. * p<.10, ** p<.05, *** p<.01.
Source: Authors.

In addition, we used the poolablility test to decide whether to use a Pooled OLS model or State Fixed Effect OLS model (see Appendix Table 3).[16] The poolability test results reject the null hypothesis of intercept homogeneity (i.e. pooling the sample together) at the 1% level, indicating that the LSDV model with state effects as well as state and year effects together favours the LSDV model over the Pooled OLS model. Therefore, we chose the LSDV model over the FEM and Pooled OLS model.

Step-wise regression is followed in the calculation of the LSDV (State Fixed Effects OLS model) model through Model (1) to Model (6), where Model (2), Model (3), and Model (6) capture both state and year effects.[17] The 99% or 100% score of the R^2 in Model (1)–Model (6) suggest the fit is good. The LSDV model estimates indicate the association between the SSCDI and GDP is positive and statistically significant in Model (1) and Model (2) with state effects and year effects. As the variables are in log scale, the estimated coefficients present elasticity. Therefore, we may conclude that the improvement in the solar supply chain may lead to high income, *ceteris paribus*, in Indian states.

Eighth, we include states' previous years of income growth (by taking a lag of state GDP) as an explanatory variable along with the SSCDI index in Model (4)–Model (6) in Table 5. The estimated results show that the association between the SSCDI and GDP is still positive and statistically significant in Model (4). However, the magnitudes of the estimated coefficients of the LSDV model change when we include a lag of state GDP. Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are used to show the statistics of good fit in Model (4)–Model (6), which shows that Model (4) and Model (5) are the most appropriate-best fit models.

Ninth, statistically significant estimated coefficients of the NER states in Model (2)–Model (6) (Table 5) suggest that the NER states need to improve solar supply chain development in order to enhance the state GDP growth. The development of the solar supply chain across the NER states also has several policy implications.

In addition to making improvements in the SSCDI in the study period, the top performing NER states in the SSCDI, Mizoram and Sikkim, have also actively participated in implementing solar energy policies and capacity installations. The Sikkim government has also set up a Unified Solar Rooftop Web Portal (USRWP) to accelerate the deployment of GRPV

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[16] See Appendix 2 for the methodology.

installations in the state.[18] In 2017, Mizoram adopted its own solar power policy targeting 80 MW of solar deployment by 2021-22 to meet the 100 MW target set by the Government of India and to achieve the Solar Renewable Purchase Obligation of 10.5% by the end of 2021-22 (Power & Electricity Department, Government of Mizoram, 2017).

Between 2014 and 2020, the NER states adopted several policies, like the Grid Interactive Rooftop Solar PV Power Policy, Solar Power Policy, and Grid Interactive Distributed Solar Energy Systems, in order to tap the potential of the emerging revolution in solar energy and to leverage the advantages of solar energy policies and schemes, such as the NSM. The NER states also notified regulations for net metering/feed-in-tariff mechanisms. With support from state and central government schemes, benefits, financial aid, and tax and fee exemptions, amongst other concessions, the NER states could increase their solar power deployment to 126.57 MW in 2021. To promote the solar PV manufacturing industry in NER states, the government is also setting up grid-connected solar power plants of up to 2 MW under the PM-KUSUM scheme, which requires manufacturers to use domestically manufactured modules. Solar energy capacities installed in the NER under both state- and central-level schemes are still low as compared to other Indian states. Strong economic structure, better law and order systems, and a cohesive society and business environment, along with proactive planning for implementing solar energy policies and promoting the installation of domestic capacities in the NER, would play a vital role in establishing regional solar supply chain and production networks.

5.2. Determinants of regional solar supply chain development: India and ASEAN Member States

The scores of the estimated composite index (SSCDI) and the corresponding ranks for India and ASEAN are presented in Table 6. The following observations are worth noting.

First, the top ASEAN countries in the SSCDI were Singapore, Malaysia, and Viet Nam in 2021, whereas the bottom three countries were the Lao PDR, Myanmar, and Indonesia.

Second, the rank in the SSCDI of some of the ASEAN countries, such as Brunei Darussalam and Indonesia, declined over the periods 2010 and 2021. The ranks of other ASEAN Member States like Cambodia, the Lao PDR, Thailand, and Viet Nam improved between the years 2010 and 2021. Singapore and Malaysia consistently occupied the top two

[18] For details, see https://usrp.sikkim.gov.in/.

ranks since 2010. Meanwhile, India's rank improved from being in the bottom three (from rank nine) to being ranked seventh from the period 2010 to 2021 (Figure 8 and Figure 9).

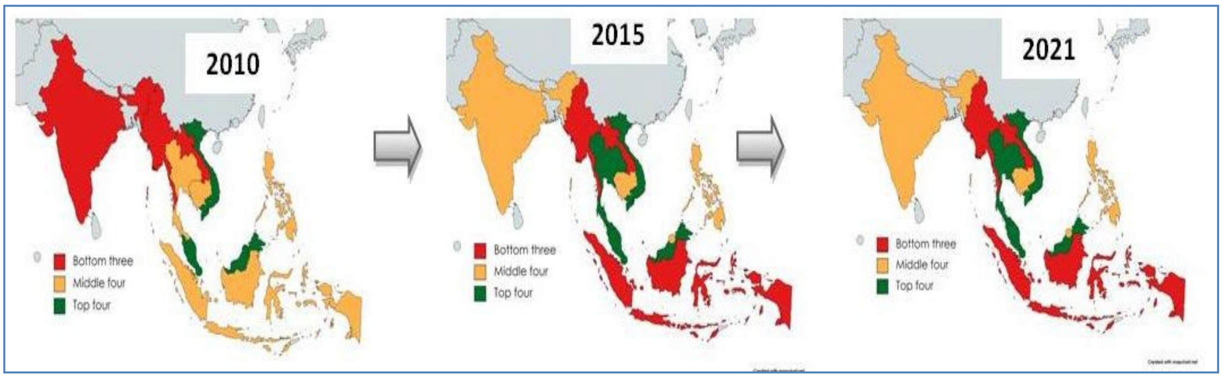
Table 6: India and ASEAN in the SSCDI

Country	2010 Index	2010 Rank	2015 Index	2015 Rank	2021 Index	2021 Rank
Brunei Darussalam	3.23	3	2.76	5	2.61	6
Cambodia	2.2	6	2.63	6	2.63	5
India	2.08	9	2.2	8	2.17	7
Indonesia	2.15	8	2.14	10	1.94	11
Lao PDR	1.95	10	2.11	11	2.08	9
Malaysia	4.18	2	3.81	2	3.46	2
Myanmar	1.53	11	2.16	9	2.07	10
Philippines	2.19	7	2.2	7	2.12	8
Singapore	12.79	1	12.72	1	12.93	1
Thailand	2.91	5	2.93	4	2.76	4
Viet Nam	2.98	4	2.97	3	2.9	3
Rank correlation coefficient	0.927*** (for 2010–2015)			0.955*** (for 2015–2021)		

***Significant at the 1% level.

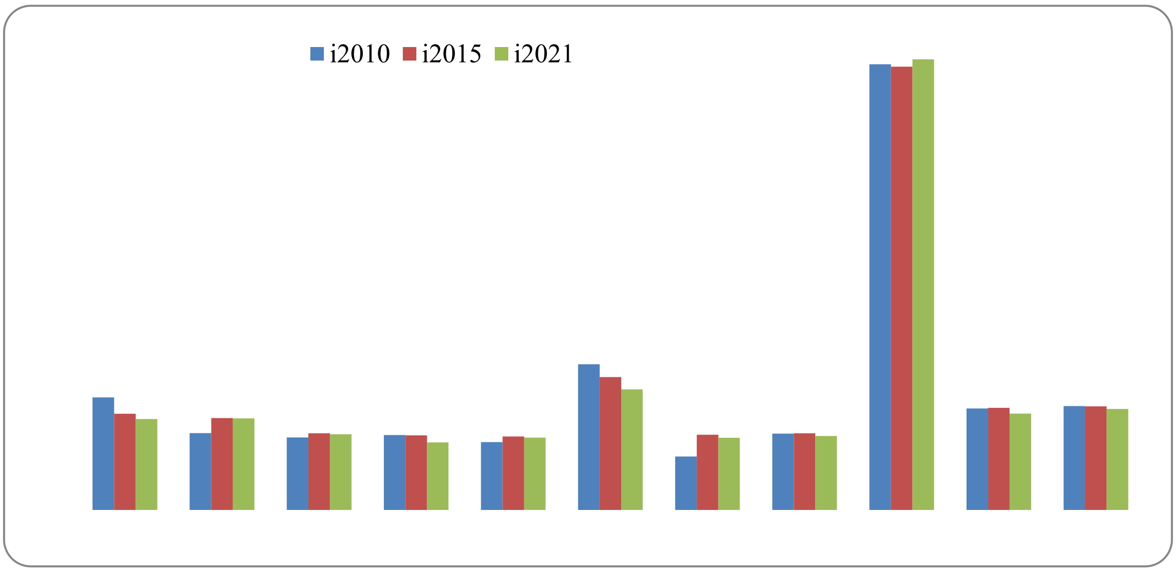
Source: Authors.

Figure 8: ASEAN Member States and India in the SSCDI over Time



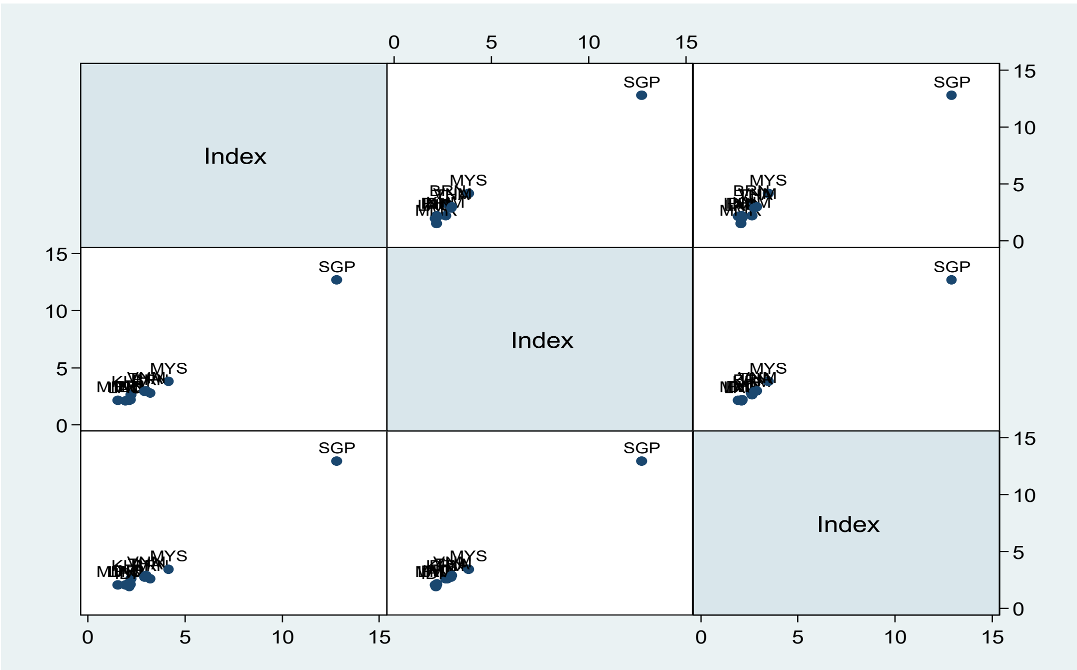
Source: Authors.

Figure 9: India and ASEAN Member States in the SSCDI



Source: Authors.

Figure 10: Scatter Diagrams of the SSCDI for India and ASEAN



Source: Authors.

Third, the Spearman's rank correlation coefficients clearly show that the ASEAN Member States' positions in the SSCDI did not change (0.927 for the period 2010–2015 vis-a-vis 0.955 for the period 2015–2021), thereby showing a high scale of rigidity amongst the member states in solar supply chain development. High and statistically significant correlation coefficients also show the strength and direction of the association of India and ASEAN

Member States in the SSCDI between years. The positions of states in the SSCDI between the years did not change and this is well captured in the scatter diagrams in Figure 10.

Table 7: Estimated Weights of India and ASEAN Individual SSCDI Indicators

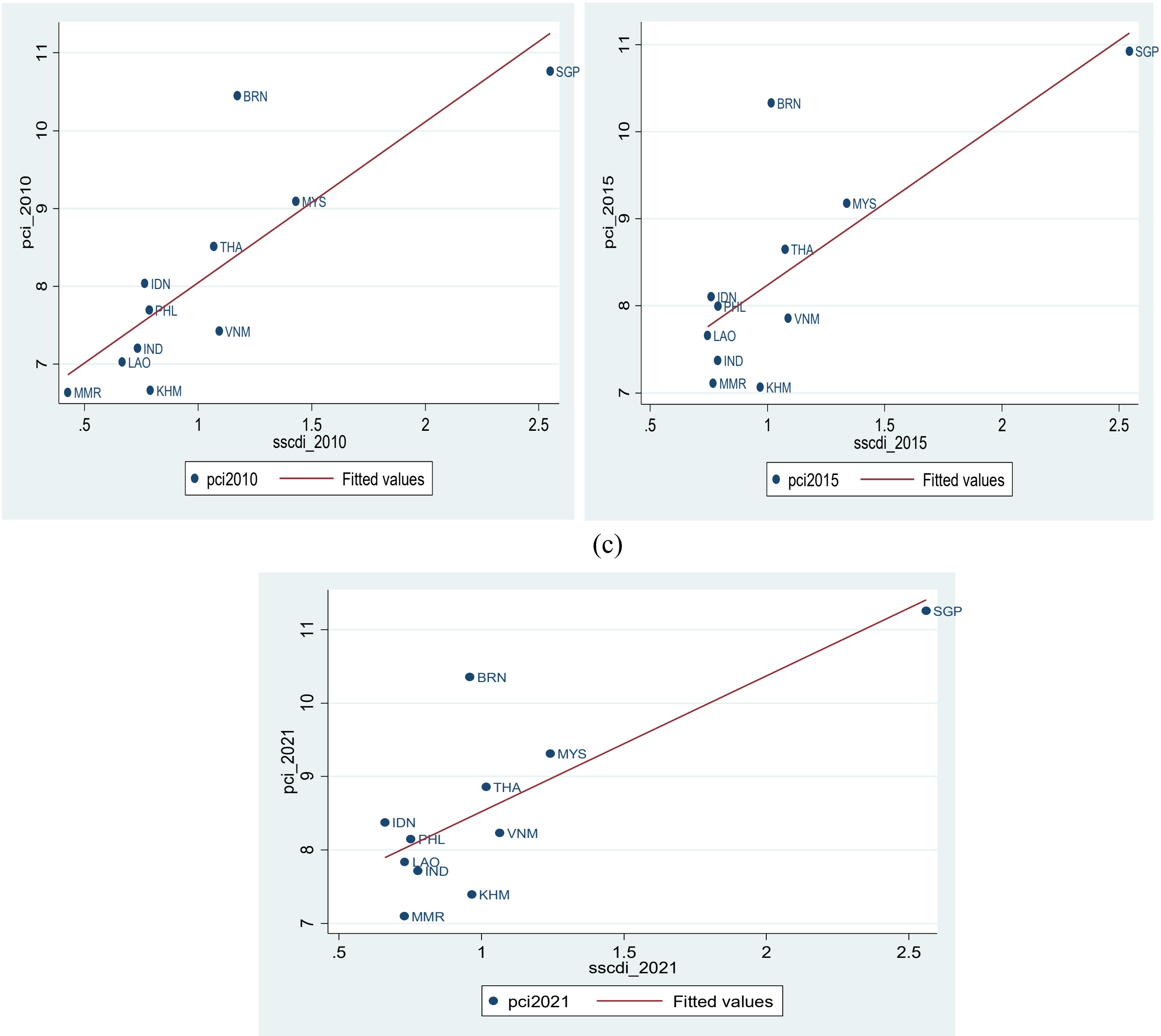
S. No.	Indicator	2010		2015		2021	
		w	*r*	*w*	*r*	*w*	*r*
1	Rail lines (rail)	0.0461	13	0.0365	13	0.015	13
2	Liner shipping connectivity index (ship)	0.2771	10	0.2862	9	0.2805	8
3	Logistics performance index (logis)	0.3142	2	0.3029	8	0.3202	4
4	Air transport (air)	0.297	5	0.3183	5	0.3158	7
5	Container port traffic (cont)	0.2927	7	0.3228	2	0.3199	5
6	Access to internet (inter)	0.3139	3	0.3064	7	0.2679	10
7	Mobile cellular subscriptions (mobile)	0.286	9	0.2213	11	0.186	11
8	Access to electricity (elec)	0.2305	12	0.2055	12	0.1755	12
9	Renewable energy consumption (re)	0.2935	6	0.3513	1	0.3203	3
10	Trade openness (trade)	0.3096	4	0.3185	4	0.3189	6
11	Foreign direct investment (fdi)	0.2322	11	0.2288	10	0.2681	9
12	Human Development Index (hdi)	0.3157	1	0.3183	6	0.3386	1
13	Patent applications (pat)	0.2896	8	0.3213	3	0.3236	2
Rank correlation coefficient	0.57*** (for 2010-2015)	0.80*** (for 2015-2021)			0.66*** (for 2010-2021)		

w = weight, r = rank.
Source: Authors.

Fourth, the weights of individual indicators in building the composite index for India and ASEAN Member States changed over time (Table 7). Similar to the Indian states' composite index, a single indicator did not pick up most of the strength. The mix of weights over time clearly suggests the changing development structure of the countries in the solar supply chain. In 2021, the top three important indicators in the India-ASEAN SSCDI were the Human Development Index, patent applications, and renewable energy consumption. Although the indicator *hdi* maintained the number 1 position in 2010, the second and third positions were taken by the logistics performance index and access to the internet in 2010, according to the PCA. This indicates that solar supply chain development is accompanied by a better standard of living, research and development, and environmental strength.

Figure 11: Link between the SSCDI and Per Capita Income of India and ASEAN, 2010–2021

(a) (b)



Source: Authors.

Air transport connectivity and trade openness are other important connectivity and economic parameters for the development of the solar supply chain. The results of the estimated weights of the India-ASEAN SSCDI also suggest that a clean and decent environment is a must for the development of the solar supply chain, which has been amply clear from the strengths of the weights of the individual indicators.

Fifth, the SSCDI helps to assess the position of a country relative to others concerning the solar supply chain. Correlating the SSCDI with per capita income shows that countries with a high SSCDI would be expected to have high income per capita (Figure 11). Most countries in Figure 11(a) to 11(c) are close to the trend line, and the fits are relatively robust in these cases as well in all three years.

The estimated scores of the SSCDI (composite index) and statistically significant estimates of the Spearman's correlations between the years for Indian states and ASEAN Member States and India as a whole show similar results, thus indicating our indices are robust.

Needless to add, constructing the state-wise SSCDI is an intricate task and has certain limitations. First, the main constraint is the choice of indicators and parameters, as the literature on supply chain development using a composite index is scant. Second, the availability of continuous data for parameters representing the indicators is also a major constraint. Third, we made the variables unit-free before constructing the index, but we did not construct or define the range for PCA. Fourth, the PCA's dimensionality reduction also results in information loss. Notwithstanding the limitations, the SSCDI constructed in the paper can be used in future studies for tracking the trends for ASEAN Member States or any other country, allowing for more informed decision-making in predicating a regional solar supply chain. As mentioned in Section 3, the list of parameters is not exhaustive and, therefore, the index can be modified with a more indicative set of parameters to capture a country's capability for securing a regional solar supply chain.

6. Conclusions

A reliable, resilient renewable energy supply chain is essential for meeting decarbonisation targets. The growth of the domestic manufacturing capacity of wind and solar supply chains is also a major opportunity to improve national energy security. Economies looking to reduce concentration or remove their dependency on China and the associated investment in Southeast Asia must cooperate to minimise the increased costs of diffuse solar manufacturing supply chains. A strong economic structure law and order system and a cohesive society and business environment can play a vital role in predicting regional solar supply chain and production networks. Using the same method, a composite index was constructed for India and ASEAN countries. The results of the India-ASEAN SSCDI are in line with the Indian states' estimated scores and indicate that a better standard of living, research and development, and environmental strength are important parameters for securing the solar supply chain. A clean and decent environment is a must for the development of the solar supply chain, which is reflected in the strengths of the weights of the individual indicators of both composite indexes.

The estimated scores of the Indian states' SSCDI and India-ASEAN SSCDI and Spearman's correlations results between the years for Indian states and India-ASEAN Member States indicate that our index is robust.

In addition, the study also suggests that requisite policies need to be undertaken to facilitate the solar supply chain in Indian states, particularly in the NER, leading to the enhancement of the state economies and regional integration with Southeast Asia. Similarly, requisite policies need to be undertaken to facilitate the solar supply chain in ASEAN Member States. By keeping the NER at the forefront, the focus must be placed on building regional solar supply chain or production networks in the NER-Southeast Asia region as the resource potential is huge, ambitions are high, and therefore, leveraging policy support will help reduce technology costs, resulting in greater inter-regional connectivity whilst moving towards a low-carbon growth path.

To realise the potential of solar energy connectivity amongst the NER and ASEAN, it is imperative to reinvigorate existing institutions and provide consistent policy support. Here are multiple types of policies that can support domestic solar manufacturing, and coordination between multiple central and state governments and regional actors will be critical.

- Manufacturing production support: Tax credits tied to the production volumes of different supply chain segments can directly offset higher costs of manufacturing in India and Southeast Asia until domestic producers reach a sustainable scale.
- Capital expense and factory support: Considering that the average selling prices of modules and their components on the market today are very close to the manufacturing costs, an expected low return on investment in the PV supply chain will dampen private sector investment. The high initial investment volume combined with the time to build and ramp up production capacity for upstream materials, components, and modules makes the cost of capital a critical hurdle. Removing this barrier by providing sufficient and rapidly deployable capital in the form of grants, loans, or tax credits would encourage private-sector investment in domestic manufacturing, as the industry would be more competitive in a global marketplace.
- Safeguard tariffs and/or anti-dumping/countervailing duties: Trade policy can improve the domestic competitiveness of specific segments of the supply chain by increasing the cost of competing imports. However, this can create higher costs for deployment. Trade policy should be coordinated so that protection for individual segments of a supply chain does not negatively impact the competitiveness of domestic upstream or downstream supply chain segments.

- Policies supporting consistent and growing deployment: Policies such as the India-Southeast Asia renewable electricity investment tax credit can increase domestic demand, forming a strong and growing customer base for the local manufacturing sector. This will support greater utilisation of any newly built supply chain capacity. As deployment increases in future decades, the supply chain can expand from the established base and take full advantage of the growing scale: to improve costs, increase geographic and corporate diversity, and, therefore, minimise risk for future investment across the supply chain.

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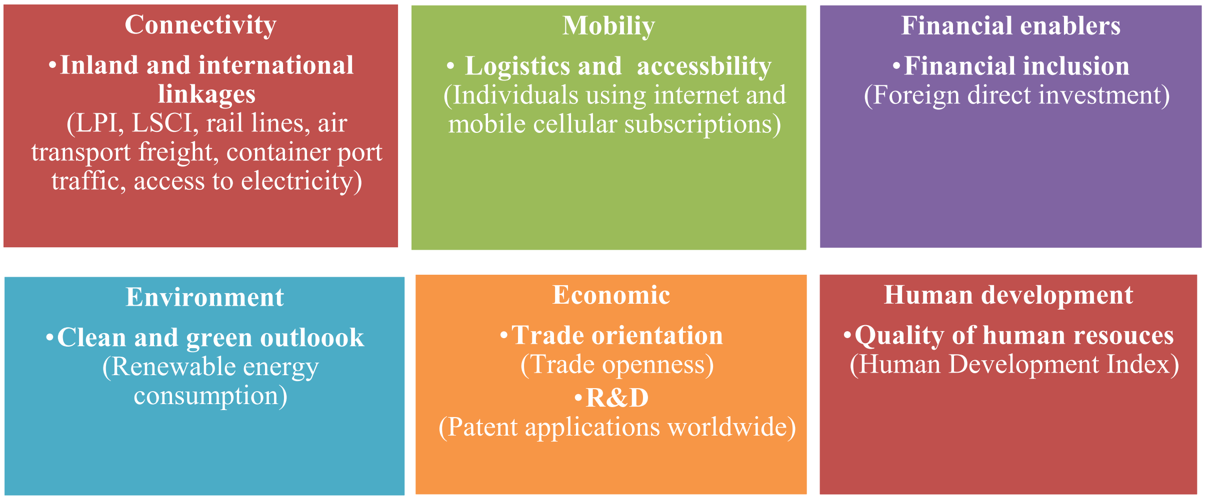
Appendix Figure 1: Framework of the Solar Supply Chain Development Index for India and ASEAN Member States



Source: Authors.

Appendix Table 1: Solar Supply Chain Development Indicators

S. No.	Parameter	Indicator	Description	Data Source
1	Economic	Industrial base (ip)	Number of factories: The number of factories is used to capture each state's industrial performance during the sample period.	ASI, various issues
		Trade orientation (to)	Export openness is used to measure the extent to which a state is engaged in global trading systems.	Economic Survey, various issues
		R&D (rd)	Patents filed: Patents filed is used to capture the state's performance in the field of research and development (R&D).	India Patent Office Annual Report, various issues
2	Environment	Forest coverage (fc)	The forest ecosystem is used as an indicator of environment as it helps store carbon and provides vital natural resources.	Handbook of Statistics, RBI
		Renewable energy (re)	Renewable energy capacity is as an indicator for environmental sustainability as it dampens GHG emissions. (Includes renewable energy sources, such as solar energy, wind energy, bio-power, and waste energy, excluding hydro)	Handbook of Statistics, RBI
3	Connectivity	Access to ports (ports)	Access to ports indicates the ports connectivity with hinterland and is a crucial link for access to global marketplace. We have considered the	Authors' own

S. No.	Parameter	Indicator	Description	Data Source
			number of land ports, airports, seaports, etc.	
		Spread of highways (high)	Length of national highways is an important indicator of economic development and social integration of cities, towns, and villages in the country.	Handbook of Statistics, RBI
		Length of railways (rail)	Length of railways indicates the overland connectivity of cities, towns, and villages of the country.	Handbook of Statistics, RBI
		Availability of electricity (ea)	Availability of electricity is a precondition for connectivity and an important indicator of economic development. We have taken the per capita consumption of electricity.	Handbook of Statistics, RBI
4	Financial enablers	Capital expenditure (cs)	Capital expenditure is an indicator of the long-term financial planning, revenue potential, and production capability of an economy.	Handbook of Statistics, RBI
		Financial inclusion (fi)	Access to finance is an indicator of ease of doing business and stimulates entrepreneurship, innovation, and productivity. We have taken access to banks.	Handbook of Statistics, RBI
		Business capability (bc)	State-wise per capita gross direct premium-general insurance.	Handbook on Indian Insurance Statistics, IRDAI
5	Mobility	Digital prowess (dp)	Digital prowess is an important indicator of mobility as it enables users to have a seamless, safer, and more flexible mobility experience.	Handbook of Statistics, RBI
		Access to telephones (tel)	Access to telephones is an important catalyst of mobility as it reflects the ability of the users to communicate anytime, anywhere, and with anyone.	Handbook of Statistics, RBI
6	Human development	Standard of living (sl)		Handbook of Statistics, RBI

S. No.	Parameter	Indicator	Description	Data Source
			Human development quality represents the quality of health, education, and standard of living.	
		Mortality (mor)	The infant mortality rate is a very important indicator of human development as it reflects the living conditions and poverty status of the population.	Handbook of Statistics, RBI
7	Social cohesion	Law and order (lo)	Law and order reflect the practices and customs that deal with crime, business, social relationships, and social integration of a state/economy.	Annual Report, Home Ministry, various issues
		Business environment (be)	The industrial environment reflects the overall economic, regulatory, social, and political connectedness and solidarity of an economy.	Annual Report, Home Ministry, various issues

Source: Authors' compilation.

Appendix Table 2: Solar Supply Chain Development Indicators for India and ASEAN

S. No.	Parameter	Indicator	Description	Data Source
1	Economic	Trade openness (trade)	Trade (% of GDP): Trade is the sum of exports and imports of goods and services measured as a share of GDP. Trade openness is used to measure the extent to which a country is engaged in the global trading systems.	World Development Indicators
		Patent applications (pat)	Patent applications, resident plus non-resident (per 100,000 population): Patent applications are worldwide patent applications filed through the Patent Cooperation Treaty procedure or with a national patent office.	World Development Indicators
2	Environment	Renewable energy consumption (re)	Renewable energy consumption (% of total final energy consumption): Renewable energy consumption is the share of renewable energy in total final energy consumption. (Includes renewable energy sources, such as solar, wind, biomass, and waste, excluding hydro)	World Development Indicators
3	Connectivity	Logistics performance index (logis)	Logistics performance index: The logistics performance index overall score reflects perceptions of a country's logistics based on the efficiency of the customs clearance process, quality of trade- and transport-related infrastructure, ease of arranging competitively priced shipments, quality of logistics services, ability to track and trace consignments, and frequency with which shipments reach the consignee within the scheduled time.	World Development Indicators
		Liner shipping connectivity index (ship)	Indicates how well countries are connected to global shipping networks.	World Development Indicators
		Rail lines (rail)	Rail lines (total route-km/million population): Rail lines are the length of railway route available for train service, irrespective of the number of parallel tracks.	World Development Indicators
		Air transport (air)	Air transport, freight (metric ton-km) per million population: It is the volume of freight, express, and diplomatic bags carried on each flight stage.	World Development Indicators
		Container port traffic (cont)	Container port traffic (TEU per 100 population): It measures the flow of containers from land to sea transport modes, and vice versa.	World Development Indicators
		Access to electricity (elec)	Access to electricity (% of population): Access to electricity is the percentage of the population with access to electricity.	World Development Indicators

S. No.	Parameter	Indicator	Description	Data Source
			Electrification data are collected from industry, national surveys, and international sources.	
4	Financial enablers	Foreign direct investment (fdi)	Foreign direct investment, net inflows (% of GDP): Foreign direct investment is the net inflows of investment to acquire a lasting management interest (10% or more of voting stock) in an enterprise operating in an economy other than that of the investor. It is the sum of equity capital, reinvestment of earnings, other long-term capital, and short-term capital as shown in the balance of payments.	World Development Indicators
5	Mobility	Access to internet (inter)	Individuals using the internet (% of population): The internet can be used via a computer, mobile phone, personal digital assistant, games machine, digital TV, etc. Internet users are individuals who have used the internet (from any location) in the last 3 months.	World Development Indicators
		Mobile cellular subscriptions (mobile)	Mobile cellular subscriptions (per 100 people): Mobile cellular telephone subscriptions are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology.	World Development Indicators
6	Human development	Human Development Index (hdi)	Human Development Index: Human development quality represents the quality of health, education, and standard of living.	United Nations Development Programme

Source: Authors' compilation.

Appendix 1

Robustness Check Methodology

The methodology for the alternate index construction is based on the following:

$$SSDCI = \frac{(Actual - Min)}{(Max - Min)}$$

where Actual is the actual value of the index for a state in year t;

Min is the minimum value of the index in year t

Max is the maximum value of the index in year t

Appendix 2
Least Square Dummy Variable Model

To estimate the impact of solar supply chain development on Indian states' economic growth, we use a Least Square Dummy Variable (LSDV) model by taking the state effect and time effect as given in equation (1) using data for the years 2010, 2015, and 2021.

$$ln\,Y_{it} = \beta_0 + \beta_1 lnX_{it} + \beta_2\,D_i + \beta_3\,t + \beta_4\,Y_{i(t-1)} + u_{it} \quad (1)$$

where i is the Indian state, t is the time period,
Y_{it} is the GDP of the Indian state i at time t
X_{it} is the solar supply chain development index of the state i at time t
D_i is the state fixed effect
t is the year effect
$Y_{i(t-1)}$ is the GDP of the Indian state i at time t-1
u_{it} is the random error

We follow a step-wise regression analysis to calculate the LSDV state fixed effect OLS estimates i.e. we create dummies for states and these state dummies are binary variables that will capture all state-specific characteristics and will control for a state's overall level of SSCDI. First, we convert the SSCDI and GDP of the Indian state into logs. Second, we regress the SSCDI on the GDP of the Indian state without a constant. Third, we regress the SSCDI on the GDP of the Indian state with a constant. Fourth, we regress the SSCDI on the GDP of the Indian state with a state effect and year effect. We repeat the same steps by including the lagged state GDP explanatory variable.

Appendix 3
Poolability Test

The OLS model is the null hypothesis of the poolability test

$$ln\,Y_{it} = \beta_0 + \beta_1 lnX_{it} + \ u_{it}$$

where i is the Indian state, t is the time period,

Y_{it} is the GDP of the Indian state i at time t

X_{it} is the solar supply chain development index of the state i at time t

u_{it} is the random error

The LSDV State Fixed Effect and Year Effect model is the alternative hypothesis

$$ln\,Y_{it} = \beta_0 + \beta_1 lnX_{it} + \beta_2\,D_i + \beta_3\,t + \beta_4\,Y_{i(t-1)} + \ u_{it}$$

In other words, we test for the presence of individual effects i.e. there is heterogeneity in the data.

Therefore,

H0: Homogeneity (pooling the sample together)

H1: Heterogeneity (different coefficients for all states and years)

For the poolability test, we first run the LSDV model by taking the state effect as given in equation (1) using the data for the years 2010, 2015, and 2021 in Appendix 2. Next, we check whether Pooled OLS or the LSDV model with state effects as well as both state effects and time effects are most applicable. Rejecting the null hypothesis indicates that the pooled OLS model in not significant i.e. the same coefficients are applicable for all individual states and times. Failing to reject the null hypothesis indicates that the no panel models need to be specified, as all individuals are sufficiently homogeneous.

Appendix Table 3: Poolability Test Results

Estimated Model	F statistics	P>F
Model 1	37.59	0.00
Model 2	239.86	0.00
Model 3	1253.07	0.00
Model 4	11.05	0.00
Model 5	44.76	0.00
Model 6	21.61	0.00

Note: P values: * p<0.10, ** p<0.05, *** p<0.001
Source: Authors.

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