Technology and policy co-evolution: the case of utility-scale solar in India

Senjuty Bhowmik[1], Aleh Cherp[1,2], Vadim Vinichenko[3], Lola Nacke[3]

Abstract

India has consistently set ambitious renewable energy targets to meet rising electricity demand and reinforce its commitment to climate action. Achieving these targets relies heavily on the rapid and sustained adoption of solar technology, particularly utility-scale solar, which has historically driven most of the country's solar growth. However, recent regional stagnation in expansion highlights the challenges of sustaining momentum and scaling adoption. We examine the role policies have played in driving solar technology growth in India. Drawing on literature on technology growth and policy mix, we examine what policies have evolved along the S-curve, both national and sub-nationally. We systematically identify the types of barriers that emerged as solar technology grew, and the policy mix that were used to address these challenges. We find that policy responses have become increasingly diverse, dynamically adapting over time to address new and shifting priorities at different phases of technology growth. These evolving priorities are also addressed with distinct sets of policy instruments. Furthermore, even as solar technology costs have declined, we observe that the number of policies has continued to grow, suggesting that cost reductions alone are insufficient to sustain growth. We also show how solar technology, policies, and politics have co-evolved in the case of utility-scale solar in India. We find that while changes in the policy mix can drive growth, they also reflect the challenge policymakers face in balancing multiple and at times conflicting priorities. Changes in the policy mix that revolves out of the need to navigate these competeing interests can introduce hidden costs that slow technology adoption, despite positive cost developments earlier. This analysis provides an overview of the co-evolution of technology and policy, underscoring the importance of integrating policy and political considerations when projecting technological growth. Our findings highlight that relying solely on cost-based assumptions can prove inadequate. Finally, we offer a perspective from a developing country context, where similar research has been limited, and where policymakers balance the complex task of meeting rising electricity demand, advancing electricity market liberalization, and renewable energy integration.

[1] Department of Environmental Sciences and Policy, Central European University, Vienna, Austria
[2] International Institute for Industrial Environmental Economics, Lund University, Lund, Sweden
[3] Department of Space, Earth and Environment, Chalmers University, Gothenburg, Sweden

1. Conceptual framing

1.1 Technology evolution

Technology diffusion is widely recognised to follow an S-shaped pattern of growth over time – with a slow start, steep middle, and eventual stabilisation[1–3]. The evolution of this S-curve can, therefore, be divided into distinct phases, each shaped by unique techno-economic, socio-technical, and socio-political mechanisms[4].

In the initial or ***formative*** *phase*, the technology is in its early development stage, characterized by high costs and significant uncertainties, leading to slow and erratic growth[5]. Adoption rates remain low; however, after a period of sustained experimentation[5,6], and very little opposition, the technology reaches a threshold—often defined in the literature as a share of total market adoption[7,8] or an absolute capacity level (__). At this point, the technology achieves "take-off," marking the end of the formative phase and the beginning of a period of steady expansion[9].

Following take-off, the technology enters the growth phase. One school of thought argues that the technology grows exponentially for the entirety of the growth phase driven by constant cost reductions and increasing profitability[10,11]. In fact, that the need for significant policy support diminishes, as cost reductions alone drive adoption. An emerging school of thought challenges this idea, suggesting instead that the growth phase consists of two distinct stages (Jewell and Cherp…). Initially, the technology indeed undergoes a period of rapid ***acceleration***, or exponential growth, characterised by sharply declining costs and increasing returns induced by technology learning. However, this phase is brief. After reaching an inflection point[12,13], costs and revenues begin to stabilise and the technology transitions into a prolonged period of ***stable*** and slower growth. This phase is marked by growing resistance and opposition from incumbent players and is very likely to experience occasional turning points[14] or growth pulses, which are marked by phases of acceleration and deceleration in growth[15].

Eventually, after a point, technology adoption slows down significantly due to rising marginal costs, challenges in grid and system integration, geophysical limitations, and social and political opposition[612,16]. This leads to the ***saturation*** phase, where the technology's market share plateaus and further expansion becomes minimal.

1.2 Policy evolution

There is a broad consensus that policy interventions have been crucial in driving the growth of low-carbon technologies such as solar[17]. Extensive research exists on the relationship between policy interventions and climate outcomes[18,19] (…) and technology growth (…). However, there is limited work that systematically maps the evolution of policies along the S-curve.

Previous studies have examined specific policy interventions, such as subsidies, feed-in tariffs (FiTs), and carbon pricing[20]. Some categorize these interventions into types of policy instruments, analysing them either individually[21] or collectively as a "policy mix"[22,23]. Within this policy mix literature, two main themes emerge. First, researchers focus on tracking the evolution of specific policies over time, analysing aspects like diversity, intensity or stringency[24], or simply density[25–27], or a combination of diversity and density[28]. These metrics are generally examined in relation to specific climate goals, such as pollution reduction or technological change.

Second key focus has been to evaluate the effectiveness of various policy instruments and to identify the optimal policy mix for achieving specific climate goals (___). The objective is to "provide a toolkit" for policymakers[29]. The main finding from this line of research is that "there is no silver bullet"[29]. however, there are key design elements[30,31] that contribute to a strong policy mix. For example, an optimal mix should consider interactions among policy instruments____, account for the roles of actors and institutions___, manage path dependencies by strategically introducing, removing, or adjusting policies to avoid lock-ins___, and should simultaneously address multiple barriers both at the market and system level[29].

Following the latter, in parallel, a less widespread stream of literature takes a broader perspective, moving away from focusing solely on policy mixes and instruments. Instead, they examine the evolving policy needs and overarching priorities that policymakers face as technology adoption increases[32] and technology costs decline[33]. This literature suggests that policy priorities shift due to three main factors. First, changes in socio-technical systems driven by technology-specific developments[22,34], which are somewhat universal for technologies, such as variable RE. Second, priorities are shaped by the existing context, including pre-exisiting insititutions and development goals And third, priorities are further influenced by shifting political dynamics and interests[35,36]. Similar to the optimal policy mix literature, this perspective argues that policymakers must balance and manage all these evolving priorities simultaneously[37].

Therefore, essentially, there are two main approaches to understanding policies: first, by the goals or priorities they aim to achieve, and second, by the tools or instruments used to achieve these goals. This framework of analyzing policies based on ends and means was introduced by Cashore and Howlett [38], building on Hall's [39] concepts of policy change. Research in the area of technology and policy co-evolution have gained prominence recently. However, to date, research has largely focused on developed countries, or technology cores with different capacities and similar eletcricity markets.

2. Approach and methods

2.1 Identifying technology evolution

We identify the development of utility-scale solar in India along the S-curve, by examining both technology growth phases and the evolving cost dynamics.

In terms of technology growth, first we define take-off as the point when solar achieves 0.5% of the market or system share. In other words, the technology achieves take-off, nationally and in respective states, when solar electricity generation accounts for 0.5% of total electricity supply. The year of take-off distinguishes between the formative and accelerating growth phase.

Second, we identify the phases of technology growth nationally, by fitting cumulative installations to four different growth models – Exponential, Logistic-linear, Linear and Gompertz [4,40]. We use a combination of best model fits and annual growth rates to identify the inflection point—the point at which growth transitions from exponential to a more stable, linear pattern. In other words, growth rates in the stable phase do not exceed the maximum growth rates observed earlier. The inflection point distinguishes between the period of acceleration and stable growth. We do not include the saturation phase simply because solar in India is not there yet.

We focus our analysis on technology growth phases of India as a whole. This is because of two reasons. One, technology growth within India is spatially heterogeneous. Therefore, looking at national growth phases provides a more cohesive framework for examining the technology and policy co-evolution over time. Second, solar development in Indian states have sometimes been erratic and with very narrow transition periods. And there is little ground to meaningfully disregard re-acceleration in states where growth is stalling. Nevertheless, we capture these spatial patterns of growth using 3 metrics. We measure take-off and the current status of growth to understand evolving diffusion patterns regionally and how these feed into the overall national picture. To measure the latter, we use the average maturity level from Logistic-linear and Gompertz model outputs. Systems with less than 50% maturity are classified as accelerating, those with 50-90% maturity as stable, and those with over 90% maturity as stalling[4]. Finally, we look at annual states' contribution to national capacity additions over time.

In terms of techno-economic dynamics, our primary focus is on the Levelized Cost of Electricity (LCOE), as it captures the evolving cost of producing solar electricity over time. However, we also consider two additional electricity price indicators to understand cost-competitiveness. One, solar auction tariffs (AT), which reflect the price at which solar capacity is allocated through auctions, which is a proxy for solar electricity prices. We also include the wholesale electricity price (WEP), which represents the average market price of electricity across all energy sources. LCOE data is from IRENA, WEP data is from Indian Energy Exchange (excluding transmission and distribution costs) and AT data is from Bridge to India. To ensure comparability with IRENA values, price indicators in local currencies are adjusted using the Reserve Bank of India INR-USD exchange rates. These are also inflation-adjusted using the FRED deflator.

2.2 Identifying policy evolution

We acknowledge that as a technology advance along the S-curve, a "bundle" or "portfolio" of policies evolves with it[25], forming the policy mix. To observe the temporal evolution of the policy mix, while keeping in line with previous work we adopt a two-dimension approach of interpreting policies within the mix. We classify policies based on – (i) policy priorities and (ii) policy instruments.

To do so, we use the Utility Scale Policy Database from Bridge to India, a leading consultancy in the Indian renewable energy sector. This database includes both planned and implemented policies, also covering active and terminated policies from 2004, specifically targeting renewable energy technologies. However, we focus exclusively on policies relevant to grid-connected, large-scale solar, excluding those related to rooftop, off-grid solar, or hydrogen initiatives. We also exclude policies that are/were planned but not adopted. The dataset includes policies which are legally-binding but also those are more voluntary programmes. Types of policies include regulations, plans, various initiatives or schemes and guidelines for their implementation, and finally administrative orders, which short policy documents that provide clarifications, corrections or extensions on an existing policy. All policies are not exclusively focused on utility-scale solar, but address grid-connected renewable energy as a whole. Our analysis distinguishes between national and state-level policies to identify differences in policymaking across government levels. We study 18 leading Indian states responsible for almost all of utility-scale solar installations in the country. Our final dataset includes 147 national policies and 385 state-level policies, between 2004 – April 2024, that related to the uptake of grid-connected, utility-scale solar in India.

Second, we classify policies based on their priorities. We define priorities as the intended outcomes of policies adopted with the specific aim of addressing key barriers that arise during variable RE technology diffusion, such as solar. Due to the absence of an existing system, we developed an original classification based on 5 policy priorities. To do so, we adopted a bottom-up, iterative approach. First, we identified key themes from literature and conducted an initial round of classifications manually based on the policy briefs provided by Bridge to India for each policy document. Second, we refined and aggregated these themes into broader categories, as a team. Finally, in cases where there was uncertainty about how to classify a policy, we consulted amongst ourselves to ensure consistency and accuracy. Based on this approach we identify 5 top-level policy priorities:

- **Domestic manufacturing** includes policies supporting or regulating domestic component manufacturing of technology.

- **Market creation** includes policies supporting an increase in technology demand or capacity addition.
- **System-integration** includes policies supporting the non-physical integration of the technology into existing systems.
- **Complementary technology and infrastructure** include policies supporting the physical integration of the technology into existing systems.
- **Land use and acceptance** includes policies supporting the local placement of the technology both in terms of land and local acceptance

Next, we classify policies based on policy instruments. We define policy instruments as tools of public interventions deployed to address policy priorities. We employ a 2-level classification system largely based on the classification scheme used in the NewClimate Institute's Climate Policy Database (___). When necessary, we also incorporate sub-categories from the LSE-Grantham Research Institute's Climate Change Laws of the World database (___), as well as recent contributions by Callaghan et al.[41] from the Mercator Research Institute on Global Commons and Climate Change in Berlin. Based on this approach, we identify the following four top-level policy instruments:

- **Economic instruments** include policies which requires governments to spends money.
- **Regulatory instruments** include policies where governments make rules and regulations for how different actors and entities interact.
- **Policy support instruments** include policies where governments make strategic long-term plans and creates necessary implementing bodies to implement these plans.
- **Target-setting instruments** includes policies where governments set targets to achieve broader climate or development goals.

This work on classifying solar policies in India was carried out concurrently with similar work on onshore wind in Germany. This parallel approach enabled us to develop a classification system with broader applicability (both across different RE technologies and geographical contexts), which also allows room to preserve contextual specificity. [42]

Finally, we measure the policy density to map the evolution of the policy mix and the diversity of priorities and instruments reflected in it over time. To do this we follow three steps.

(i) We identify the termination date of policies which are stated as expired in the database. In case, this information is not available, we assume that the policy was active after 3 more years from any last update on it. These updates may be amendments, additional orders, corrections or clarifications made. In cases where a policy is released on or after 2022 and has been classified expired, with no information on the date of expiry, we use 2024 as the year of expiration. Finally, we count the active policies cumulatively after removing terminated policies in a specific year. Policies repealed in a year *t* are removed from the density measurement in year *t+1* (as in Schaub et al 2022).

(ii) Each policy is counted as 1 in our policy density measure. However, if one policy has more than one priority or instruments represented within them, which is particularly common in case of instruments, we give them equal weights because there is no empirical evidence to indicate whether one priority or instrument type is more important than others for the adoption of the technology. For example, the national Wind-Solar Hybrid policy adopted in 2018 supports the development of wind and solar hybridisation but also the expansion of solar technology in the process. It also includes preferences for local content requirements (LCR) and outlines how these hybrid projects will be integrated into the electricity grid. As a result, it receives 0.25 count for each policy priority - market creation, system integration, domestic manufacturing, and complementary technology and infrastructure.

(ii) Finally, we take a snapshot of which priorities are addressed by which instruments at the two level of governance. For this, we assume that each instrument active through a policy, addresses all its corresponding priority(/ies) equally, which may not reflect the reality in practice. Ex, in Figure 6 we see targets used to implement land use priorities in states. However, in reality, states do not set land-use/ solar park targets. These emerge because state-level solar policies, which address a mix of priorities by adopting a mix of instruments, also include land acquisition guidelines and land-use planning for solar. These set capacity targets, and generally offer various support towards market creation and complementary technology developments. Nevertheless, these overlaps are relatively minor and do not alter our results significantly.

2.3 Identifying technology and policy co-evolution

After examining technology and policy evolution separately, we analyze how these two areas co-evolve. Our goal is to understand the anatomy of the S-curve by considering the influence of policies and political dynamics. We do this by observing changes in the policy mix across various phases of technology growth. Through this approach, combined with insights from process tracing, we assess whether shifts in the policy mix coincide with changes in technology growth patterns. We observe that different policy-making rationales or logics emerge as technology adoption advances. We distinguish between two sources of policy-making logics – (i) internal, that emerge from socio-technical changes within the system, and (ii) external, that emerge from political changes, development shifts and crisis. Our approach also reveals, which broader groups of actors are prioritised along the S-curve, how changes within the policy mix infuence actor interactions, which in turn influence future policy adoption and technology growth.

Table 1 Classification based on policy priorities and instruments for large scale solar in India

Policy priorities	**Themes in national policies**	**Themes in state policies**
Market creation	Policies that target capacity additions like auctions and schemes that provide incentives to solar developers for specific capacity additions, RPO targets, national level plans, etc.	Policies that target capacity additions and provide incentives to solar developers for capacity additions, RPO targets
Domestic manufacturing	Schemes with specific local content requirements Mandatory registrations Production-linked incentives	Promotion of industry, enterprises and investments in states related to promotion of domestic manufacturing.
System integration	Establishing institutions Ownership and contracts-related Other cost or tariff determination High-level long-term sectoral plans RPO and REC frameworks Captive status and open access Trade policies Dispatch rules Balancing related Curtailment Payment security measures Ancillary service regulations ISTS related	Ownership and contracts-related Other cost and tariff regulations RPO and REC frameworks DISCOM bailout Captive status and open access regulations Balancing related Ancillary service regulations ISTS related
Complementary technology and infrastructure	Promoting storage and hybrids Grid expansion and development	Promoting storage and hybrids Grid expansion and development
Land	Solar park	Solar park Land policy related to conversion, registration and usage
Other	Covid related	Covid related GST related

Policy instruments	**Level 2 instruments**
Economic	Direct investment (Public procurement, Funds to other govt entiities, R&D) Financial and fiscal incentives (Feed-in tariff, Tendering schemes, Taxes (import), Priority lending, Value Gap Funding, Capital subsidy for farmers, Transmission charge waivers, Electricity duty waivers, Reduction in development guarantee, Purchase of excess power, Return of performance security, Payment security (discom late payment surcharge, in case of curtailment) Market-based instruments (REC, Carbon credit trading)
Regulatory	Price control Obligation and compliance Sector regulations Trade policy Spatial and land use planning Production standards/ quality control Guidelines Extensions Investigations
Target setting	All targets
Policy support	Strategic planning (Ex. implementing agencies, new markets) Institution creation (Ex. High level national plans and policy frameworks)

3. Results

3.1. Technology developments

We observe that the technology grows differently at the national and sub-national/ state level. Nationally, solar PV has moved beyond the formative phase, passed a period of rapid acceleration and is now experiencing stable growth. However, sub-nationally, solar growth is spatially heterogenous. In some states, solar is still in the formative phase, in some growth is accelerating, while in other growth is stalling.

Second, the technology went through periods of growth pulses mostly at the sub-national level, but also has a uniform episode in the country. After a steady period of incremental growth in annual capacity additions, growth momentarily slows down in 2019 and 2020, nationally and across states despite favourable technology costs and auction tariff developments in the previous years and re-accelerates in 2021. Sub-nationally, annual capacity addition progresses with periods of growth spikes, noticeable in all 18 states around 2016, and less commonly around 2021 and 2012. States where growth is stalling tend to do so 2018 onwards.

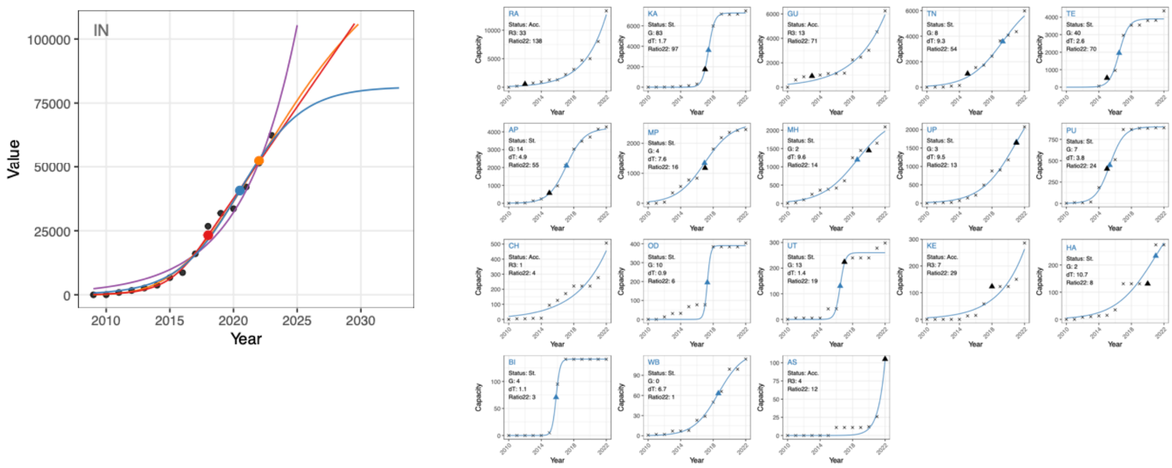


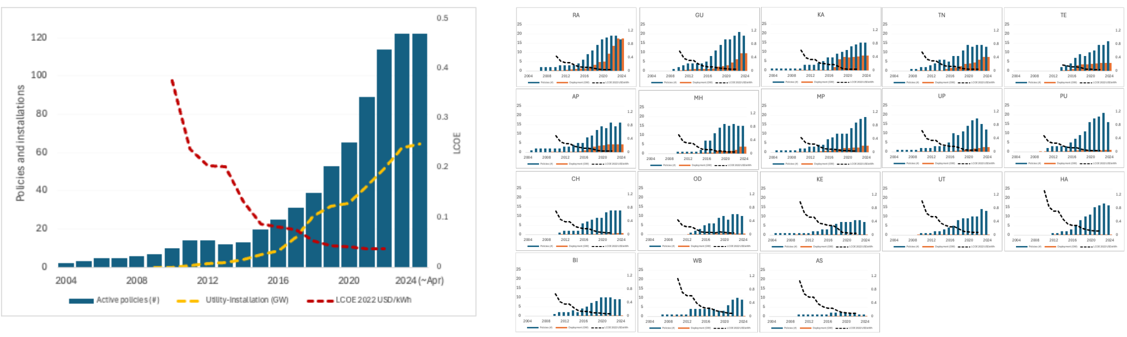
Figure 1: Solar growth in India (left) and across 18 states (right)

3.2. Evolution of the total policy mix

As solar PV advances along the S-shaped path of technology growth, a “bundle” or “portfolio” of active policies evolves with it, forming the policy mix. In figure 2 (left) we observe that despite significant improvements in technology learning, reflected in reduction in solar electricity production costs, the density of the policy mix expands. In other words, the total number of active policies associated with the technology increases. This happens not because of fewer policy discontinuations, but rather due to a steady increase in the number of new policies adopted as the technology matures. Our finding suggests that the need for policies supporting a new technology, here solar PV, does not diminish or disappear, with increased cost reduction and market share. Rather, despite favourable market dynamics, continued and more policy effort is used to drive deployment.

A similar relation evolves in leader states figure 2 (right), where the policy density increases as technology adoption grows. However, in others, the policy mix grows without a corresponding increase in technology growth, which may be attributed to patterns of sub-national policymaking in the country. The push for solar in India has primarily been driven through a top-down approach by the national government [43]. While attitude towards policymaking at the national level has focused on broader objectives (example, energy security, international policy trends, global and domestic political ambitions and economic and sectoral developmental goals), state-level policymaking translates into the “on-ground” execution of national objectives (...), considering contextual factors like resource, technology and infrastructure availability, and the nature of power demand within each state (...). Policy diffusion have not always followed a linear path from national to state adoption. Instead, certain policies are first introduced or piloted in pioneering states, or simply states are proactive in adopting certain policies. Once a policy is established at the national level, it begins to spread more rapidly across states, mostly because states are required to do so. For instance, the policies encouraging farmers to produce and use solar energy (as prosumers) for agricultural purposes were first adopted by Gujarat (*Suryashakti Kisan Yojna*) and Maharashtra (*Mukhyamantri Saur Krushi Vahini Yojana*) in 2018, predating the similar national-level (*Kisan Urja Suraksha evam Utthaan Mahabhiyan*) KUSUM scheme, which was launched in 2019. That said, the speed at which a certain policy is adopted or diffuses across states may vary, but over time, states have adopted similar policies over time (___).

Figure 2: Evolution of policy density, LCOE and technology adoption in India (left) and in states (right)



3.2.1 Diversity of priorities and instruments within the policy mix

With increased solar PV adoption, Indian policymakers, both at the national and sub-national level, pursued multiple priorities simultaneously which were addressed through a wide selection of policy instruments. We observe that the policy mix not only becomes denser but also more diverse, expanding both in the number and range of priorities and instruments used. Figure 3**,** panel, show initially only one priority and instrument, which over 21 years evolves into a mix of five broad priorities and 15 second-level instruments. Therefore, as technology matures, new issues and objectives emerge, and the limitations of earlier policies become apparent, leading to policy learning and prompting both amendments and the adoption of new policies. For example, in later years, new policies have been introduced to support complementary technologies and infrastructure critical for renewable energy adoption. These not only focus on addressing the variability of solar power generation with incentives for energy storage and the development of experimental or hybrid technologies, but also on expanding the capacity of existing systems, such as through grid expansion. Simultaneously, legal amendments during this time like the 2022 Electricity Rules (Late Payment Surcharge and Related Matters), aimed at facilitating smoother grid integration and safeguarding developers from the increased financial risks associated with Discoms' delays in payments.

Like priorities, the mix of policy instruments becomes increasingly complex, with a particularly notable expansion in regulatory measures. In the case of solar PV in India, this diversification is partly driven by technology-specific requirements, including the issuance of procurement guidelines, the establishment of production standards, land use planning, and compliance obligations related to local content regulations (LCR) and renewable purchase obligations (RPOs). Other regulatory instruments are shaped by the context of a non-liberalized electricity market, such as price controls and setting up markets for electricity and renewable energy certificate (REC) trading. Additionally, some instruments emerge from a combination of technology-specific and contextual factors, such as sectoral regulations that support the overarching goals of large scale RE deployment within a state-controlled power market context.

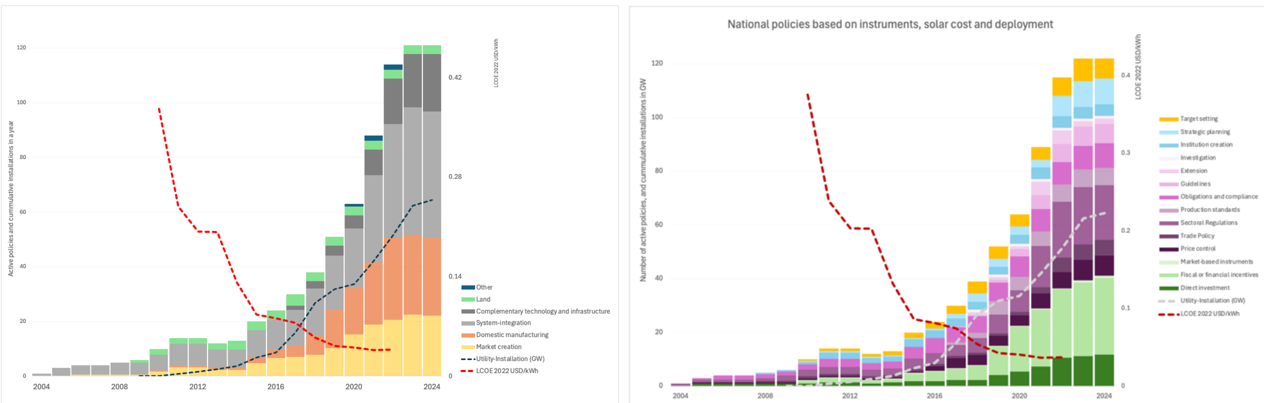


Figure 3: Priorities (left) and instruments (right) in the active policy mix at the national level

3.2.2 Dynamic evolution of priorities and instruments within the policy mix

Policy priorities and instruments evolve dynamically along the S-curve, reflecting a continuous shift in policymaking logics as the technology matures. These logics may be specific to the technology or shaped by evolving political and external events, as further discussed in Section 2.3. The dynamic evolution of priorities and instruments can be visible through their changing share within the policy mix. Among policy priorities, for example, we observe a growing focus on domestic manufacturing and a steady rise in support for complementary technologies in recent years. In contrast, the emphasis on land policies initially grew but has since declined at the national level. System integration policies, however, have consistently dominated, highlighting the ongoing market reforms in India's power sector and the pressing need to address structural challenges that new entrants face. For India, this means that policies must not only promote the integration of emerging technologies like solar but also establish a robust electricity market framework that supports this transition. This need is particularly critical as solar and wind energy represent the first sub-sectors in India's power market to be predominantly privately owned.

A similar dynamic evolution is visible in terms of policy instruments. At the highest level, the emphasis on economic and regulatory instruments remains steady, while the focus on policy support and target-setting instruments decreases over time (and an internal shift from institution creation to strategic planning). The shift does not imply that these latter instruments are no longer introduced, but rather that their growth relative to regulatory and economic instruments diminishes, suggesting a maturing policy framework. In the initial phase, policies focus on establishing foundational support for the new technology, including long-term target adoption and institution building, which tend to remain stable and are less frequently changed. After this foundational phase, a period of relative stability follows, with a shift toward prioritizing regulatory and economic instruments to optimize the established framework and address emerging challenges. That said, regulatory policies have continued to grow and have outnumbered other types of instruments, underscoring their importance in the given context and technology to guide and stabilise the sector as it evolves. Furthermore, it may be that policymakers are intentionally limiting the rise in policy costs by maintaining share of economic instruments and instead managing technology uptake primarily through regulatory measures. However, it is notable that policies incurring public spending on the sector does not simply disappear rather the share of economic instruments remains steady, while the priority where these instruments are directed to is likely to have temporal dynamics, depending on context. For example, reallocating public spending to support greater system integration, particularly for technologies that require funding at the peak of their learning curve, may represent a more universal approach. However, the phase of technology adoption at which these policies become necessary can evolve and will depend on the flexibility of the existing power system and nature of future energy demand. For example, with limited grid capacities and growing energy demand, such as in India, these policies are likely to pop up earlier on the S-curve. Therefore, to understand the nuances of policymaking within this specific context, we next explore which policy instruments have been used to address the key policy priorities for large-scale solar PV in India.

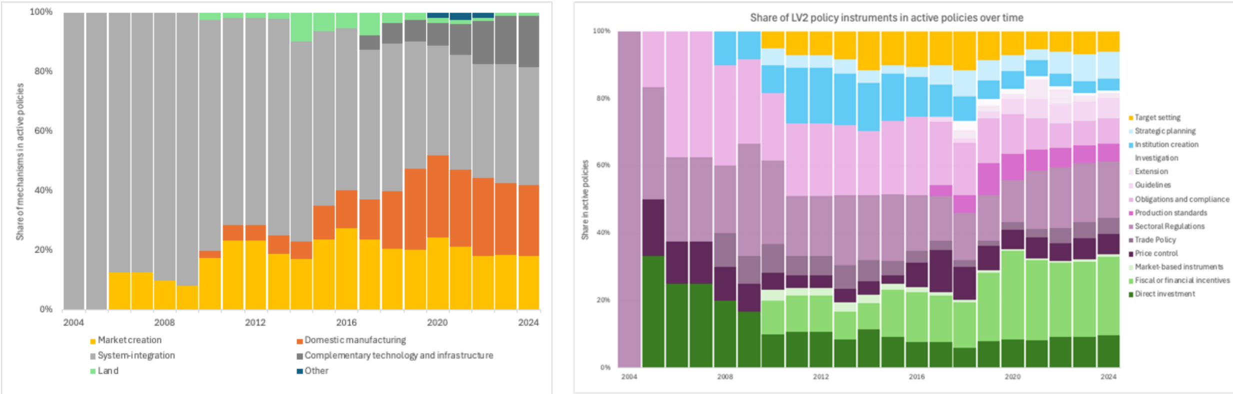


Figure 4: Share of priorities (left) and instruments (right) in the active policy mix, at the national level

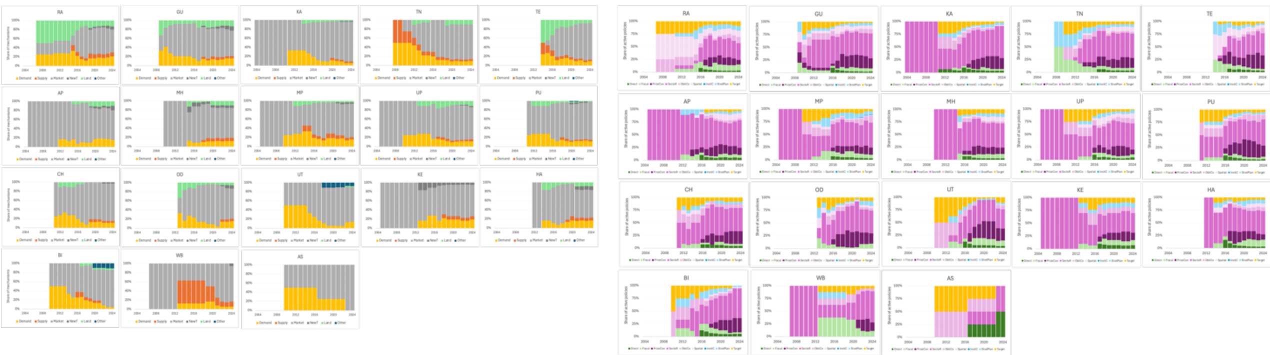


Figure 5:Share of priorities (left) and instruments (right) in the active policy mix, at the state level

3.2.3 Connecting priorities and instruments within the policy mix

While the relation between priorities and instruments within the policy mix have their own temporal dynamics, this study focuses on capturing a snapshot of this relation in the final active policy mix in 2024. Figures 6represent the distribution of policy instruments across different policy priorities both at the national panel (left) and state-level (right). We make three key observations: (i) each policy priority is addressed with a distinct set of instruments; (ii) the share of instruments addressing these priorities differs between national and state-level policy making; and (iii) national policies demonstrate a higher overall diversity of instruments and is also more dynamic.

Market creation policies rely on a balanced mix of instruments, integrating economic, regulatory, policy support, and targets to foster growth. Economic instruments include fiscal and financial incentives such as subsidies and auctioning schemes, alongside direct investments, primarily nationally, in publicly owned enterprises like CSPUs and

DISCOMs. Regulatory frameworks enforce renewable purchase obligations, compliance policies, and auction guidelines that dictate how solar energy is integrated into the grid, ensuring efficient market operations. Policy support emphasizes long-term strategic planning at both national and state levels, highlighting the significance of goal-setting to drive market development.

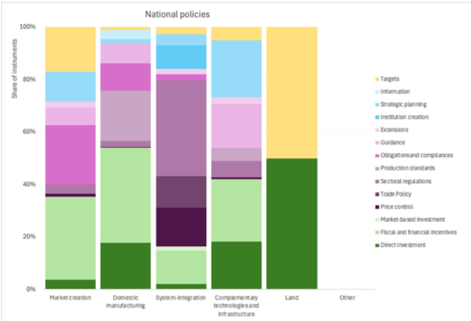
In contrast, domestic manufacturing policy is primarily dominated by economic instruments, which account for over half of the policies adopted at both levels. These include national import taxes and auction-linked production incentives, complemented by state-level electricity duty exemptions for new commercial and industrial consumers who install solar capacity for captive consumption. Regulatory measures, such as product standards and local content obligations, play a crucial role nationally, while state policies focus on promoting investment for MSMEs through strategic planning. Although target-setting is present, it is less emphasized compared to other priorities.

Policies focused on system integration are predominantly regulatory, encompassing sector regulations, price controls, and trade policies reflective of a non-liberalised electricity market at the national level. Economic instruments at the state level involve direct investments like bailouts for DISCOMs and national-level fiscal incentives linked to payment security measures, addressing the financial challenges faced by generation companies and grid curtailment issues. Market-based instruments such as REC and carbon credit trading are mainly observed at the national level. Targets setting emerge from high-level strategic planning.

Conversely, policies supporting complementary technologies and infrastructure use a balanced mix of instruments similar to market creation. Although national policies exhibit stronger support for technology growth, state-level policies concentrate on sectoral regulations, addressing emerging challenges related to variable cost dynamics. This highlights the distinct policy-making rationales at the two levels of governance – while national policies set top-level trajectory of technology growth (visible in higher policy support at the country level), the nuance of managing and implementing this growth within non-liberalised electricity market context (example, adopting balancing and grid integration policies) falls within the domain of states, visible through a higher share of regulatory instruments at the state level. Economic instruments here again consist of fiscal incentives, with direct investments for grid expansion being more prominent nationally.

Land use policies vary significantly between national and state levels due to jurisdictional distinctions. National policies promote solar parks with direct investments to state government to develop solar parks and target-setting, while state policies employ regulatory instruments focusing on land-use and spatial planning.

Lastly, other emerging priorities, such as COVID-19 impacts and GST concerns linked to the domestic supply of components for power development, have been addressed primarily through regulatory instruments, reflecting localized responses that emerged during the pandemic and are not prominently featured in the current national policy mix.



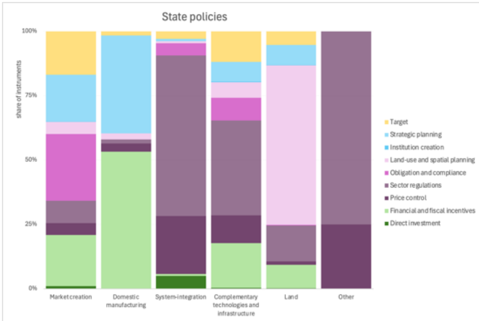


Figure 6: Distribution of policy instruments across different policy priorities both at the national (left) and state-level (right) in the active policy mix in 2024

3.3. Evolution of policy making logics along phases of technology growth

The evolution of the policy mix, with its shifting priorities and instruments, reflect distinct policy-making logics at various phases of technology growth. These logics are shaped by both technological advancements as well as changes within the political context that occur simultaneously alongside other external events. These policy-making logics provide insights into the evolving interactions between key stakeholders involved in the diffusion of large-scale solar PV in India. We capture technology and policy co-evolution over different growth phases and zoom in more closely on critical time periods to analyse these dynamics in depth. Table 2 offers a summary of technology, policy and politics co-evolution at the national level.

3.3.1 Foundational policies and pre-auction era (2004 – 2009)

Solar energy in India has had a long history, beginning in the 1970s and 1980s when the government first explored renewable energy as a solution to address energy scarcity. These early efforts primarily focused on decentralised solar projects aimed at providing electrification to rural and remote areas[44]. However, policy support and large-scale technology development remained constrained for decades. Following the start of India's economy-wide liberalization efforts in the early 1990s, a major turning point for the power sector came with the adoption of the 2003 Electricity Act (…). This comprehensive reform package aimed to encourage private participation in power generation and to incorporate a larger share of renewable energy production, among other things. Soon afterwards, in order to keep pace with global policy trends, India adopted the National Action Plan on Climate Change (NAPCC) in 2008 (…). This plan aimed to align India's development goals with climate action globally while adhering to the principle of Common But Differentiated Responsibilities under the UNFCCC framework (____). The ambition of a large-scale solar development in the country was introduced as a part of this action plan.

Therefore, between 2004-2009, the policy mix was limited in both density and essentially diversity. Policy making logics involved steering the country's power sector liberalisation efforts while also creating a foundational framework – through regulations and new institutions – to support a large-scale RE adoption. Measures introduced included sectoral regulations like RPOs, RECs, open access, and direct investments to state DISCOMs to be able to absorb new and expensive RE generation. Since technology costs were high at this stage, developers were offered attractive FiTs or generation-based incentives to encourage solar adoption.

There is very little solar adoption across states and nationally. Technology is in its formative phase. However, Gujarat emerged as the proactive "first mover," with the first solar policy adoption in the country in 2009. With a strong state support, DISCOMs within the state signed 1 GW worth of solar PPAs at significantly high tariffs of 15 INR/ kwh that would reduce to 5 INR/ kwh in the second half of the project lifetime[45–47].

3.3.2 Beginning of National Solar Mission and auction era (2010 – 2013)

In 2010, the first national solar policy was adopted. The Jawaharlal Nehru National Solar Mission (JNNSM) was launched with a goal of incentivising solar technology in three distinct phases over the next 12 years. A target of achieving 20 GW of grid-connected solar capacity was set for 2022. This saw a rapid adoption of solar policies by states, each setting up their own respective targets to contribute to the national ambition. With the first solar auction, 2010 also marked a shift in the compensation mechanism, where developers would now be compensated through a "pay-as-you-bid" model, where the winning tariff would apply for the project's lifetime. Costs and tariffs were initially high but began declining rapidly, driven by economies of scale, global technology learning and competitive solar auctions domestically.

The policy density grew during this period, nationally doubled, but the evolution of policy composition and new policy adoption remained relatively static during the 4 years, reflecting a mix of a "wait-and-see" approach. New policies were layered into previously developed frameworks without disrupting, rather supporting, existing regimes to engage. For example, established thermal power producers like NTPC began integrating solar into their portfolios, often bundling it with coal capacity additions. Both solar power developers and solar component manufacturers were incentivised, the former more intensively (through subsidies, tax benefits, cost waivers, etc.) than the latter (primarily through LCR).

Nationally, although solar technology was still in its formative phase, the sector had already gained momentum by achieving take-off, or 1% of electricity generation, in four out of 18 states. In terms of absolute capacity additions, Gujarat and Rajasthan emerged as leaders with close to 1 GW of installed capacity in each. Although supported by favourable geophysical conditions, the states experienced varying trajectories in terms of the financial outcomes for solar developers. In contrast with the latter, developers in Gujarat benefited from better performing DISCOMS, a bigger high-tariff industrialised consumer segment, but most importantly a proactive government and strong state support under the leadership of then state[47] Chief Minister Narendra Modi.

Politically, leveraging the successes in solar energy in Gujarat, we observe the rise of Modi as a political entrepreneur and a national leader in India's solar policy landscape. He later ran a successful national campaign for the country's highest office, positioning himself, among other things, as a champion of solar energy, a strong and proactive administrator with a vision of solarising India and establishing the country as a global leader in solar power.[48]

3.3.3 Acceleration in growth and shift in political regime (2014 – 2018)

The period between 2014-2018, saw simultaneous developments in technology growth, cost and tariff evolution and policy and political change. Nationally, solar achieves 1% of electricity generation and starts accelerating in 2016. 13 of the 18 states also achieved take-off. Capacity addition in this period is primarily lead by a handful of states in the south (KA, TE, AP, TN) and the west (RA, MP and GU). The southern states together contributed to more than double of total installations compared to North-western counterparts (Figure____), and KA did majority of the heavy lifting with a favourable land acquisition policy (____) and central-led solar auctions (___). In contrast, installations in GU waned after initial boost, with DISCOMs now stuck with high tariff PPAs showing reluctance to sign new ones.

Solar power costs and tariffs continued to decline rapidly and for the first time an auction in KA yield a winning tariff below the prevailing wholesale electricity price, thereby marking a very significant grid parity threshold. This meant that distribution companies in some (and subsequently more) parts of India could now expect to buy electricity from new installations at a price lower than or equal to that of other prevailing energy sources.

During this period, the policy mix grew in both density and diversity. Policy efforts focused on addressing emerging barriers to protect the interests of three main actor groups. First, policies focused on overcoming key barriers for solar developers. For example, the promotion of solar parks streamlined land acquisition, policies were introduced to manage balancing-related deviations, and the validity of un-purchased RECs was extended. However, the key policy was the adoption of competitive bidding guidelines, with central entities taking the lead in conducting auctions. MNRE released these guidelines in 2017 to unify and enhance the transparency of the solar auction process nationally. Soon after from 2018, central entities like SECI assumed the role of intermediary procurer and started conducting more auctions nationally – a trend which has since continued with temporary decline in 2021 and 2022. The key goal was to offset developers' risk of going into business with financially volatile distribution companies.

Additionally, while new policies aimed to support developers, they also sought to broaden the adopter group across new sectors, especially building synergies with those having conflicting interests. For example, to address farmers' reluctance to sell or lease land for solar installations, the government introduced the KUSUM / agriculture-focused scheme. Farmers were subsidised to act as prosumers and install solarised agricultural pumps, to be able to have uninterrupted power supply and to sell excess power back to DISCOMs and gain an additional income stream. (____ex from similar exp in EU/ Germany). Similarly, Solar-Wind Hybrid Policy was adopted not only to foster synergies between solar and wind developers but also support hybridisation of RE projects capable of providing Round-the-Clock (RTC) power to address intermittency challenges.

Second, policies focused on overcoming key barriers for state DISCOMs. DISCOMs were facing significant challenges in signing PPAs and meeting payment obligations to solar developers due to their history of poor financial health, high debt levels, and operational inefficiencies. These issues made it difficult for them to accommodate the large increase in RE capacity additions. Stuck in long-term, fixed tariffs, DISCOMs cancelled tenders in GU __ or in states like AP and TN sought to renegotiate solar contracts as technology costs declined. These posed financial uncertainty on solar developers. To address these challenges, the UDAY (*Ujwal DISCOM Assurance Yojana*) scheme was introduced, where state governments would take over a significant portion (75%) of DISCOM debt to reduce their financial burden. The scheme aimed to improve the overall health of the power sector, encourage renewable energy adoption, and ensure reliable electricity supply across the country. Additionally, as part of the KUSUM scheme, DISCOMs would receive central financial assistance to purchase excess electricity from farmers adopting solarised agricultural pumps, to support technology growth.

Third, policies were introduced to overcome key barriers for domestic solar component manufacturers. Indian manufacturers, like other global counterparts, faced intense competition from heavily subsidised, low-cost Chinese solar modules and cells (____). Initially, manufacturers were protected through the Local Content Requirement (LCR) design in solar auctions since the very first. However, this protection proved insufficient for the industry's long-term viability. The situation worsened when the US challenged India at the World Trade Organization (WTO) in 2015, arguing that the LCR violated WTO's non-discriminatory trade rules. In 2016, the WTO ruled against India in relation to a 750 MW solar power tender with a 50% LCR. In response, India introduced the CSPU scheme in 2015, under which, projects auctioned would be required to use only Indian-made cells and panels, but the power generated could only be used by government-owned companies (___). But more crucially, in 2018, India implemented a safeguard duty on solar cells and modules to protect domestic manufacturers from cheap Chinese imports (__). Similar import duty was also introduced in the US under Trump at the time (___).

While policies adapted to technological developments, they also reflected the evolving political dynamics, both nationally and globally. When Narendra Modi took office, he ushered in a shift in political priorities and forged a new coalition of interests and ideologies. First, as a strong advocate for solar energy within India, he revised the 2022 NSM target, raising the ambition fivefold to achieve 100 GW of grid-connected solar capacity by 2022. Of this, 60 GW was to come from utility-scale solar, a target India achieved 87% of by the deadline. Second, to position India as a global leader in solar energy, Modi launched the International Solar Alliance (ISA) in 2015, establishing the first international organization headquartered in India. These initiatives demonstrated India's heightened ambition in solar energy, driven by a centralised push from the national government. Consequently, in addition to policy adaptations responding to technological progress, there was a significant expansion in the active policy mix from the time Modi took office. Third, successful policy efforts at the state level, particularly in Gujarat, started to diffuse at the national level. For instance, until 2014, small solar developers in Gujarat were primarily concentrated in the Charanka Solar Park, a model championed by Modi, during his time as the leader of the state. In 2014, this model was adopted nationally as the solar park policy, with targets revised upwards in 2017.

Finally, the challenges facing India's domestic manufacturing industry were not new, but the increased policy support to this industrial group were shaped by shifts in the political ideology and lobbying by interest groups that could yield influence. Between 2010 and 2015, the manufacturing industry had appealed to the government six times for protection against foreign competition but failed to secure substantial support. In December 2017, the Adani Group's solar manufacturing division, Mundra Solar, led a coalition of five manufacturers and filed a petition with the Director General of Safeguards under the Customs and Central Excise Commission. They sought protection from foreign solar components, citing unfair competition. In 2018, the petition faced legal obstacles after a counter-petition from a solar power developer led to a temporary halt by the TN High Court. However, the Supreme Court later ratified and reinstated the safeguard duty in 2018 (____). This development marked a turning point for domestic manufacturers, driven by the consolidation of interest groups and Modi's political background in Gujarat, where he supported such business niches and emphasised domestic manufacturing, aligning with his campaign message of economic self-reliance and energy sovereignty (Bhatia 2023).

3.3.4 Temporary slowdown in growth (2019 – 2020)

After a period of accelerated capacity addition, we observe an inflection point in technology growth in 2019–2020. During this brief window, the pace of annual capacity addition slowed temporarily, despite favourable cost and tariff evolution in the immediate past. The technology transitioned into a stable growth phase. This trend is visible at both the national and sub-national levels, with a more pronounced reduction in growth in the southern states. While capacity additions in the western states continued at similar levels in 2019, installations in southern states like in KA, AP, and TE notably slowed and started stalling. In contrast, solar continued to grow in TN in 2019.

The decline in costs and tariffs also start stabilising during this period. Although module prices have decreased, the imposition of import duties offset reductions, keeping the overall cost of producing solar electricity steady. We also observe the tariff show similar evolution, perhaps both as a response to cost but also with previous auctions resulting in similar tariffs as wholesale electricity price, there is less incentive for solar developers to underbid. (Insert average annual decline rate in costs and tariff.)

The policy landscape continues to grow denser and more diverse. Policymaking logics largely followed trajectories established in previous years, with an increased emphasis on supporting domestic manufacturing and market creation at the national level along with continued support for system integration and complementary technology policies at both national and state levels. As barriers started to loom with increased technology adoption, we saw that in the previous period the government adopted policies to balancing multiple priorities and actors' interests. However, the evolving policy mix introduced contradictory tensions between two key actor groups involved, the effects of which were further amplified by the COVID-19 pandemic, temporarily slowing down growth.

While policy developments aimed to protect domestic manufacturers, they did not provide equivalent support for developers, leaving them exposed to negative feedbacks on production costs. As a result, the introduction of import taxes created conflicting pressures between two key industry groups: solar developers and domestic component manufacturers. The majority of solar development up to this point had relied on cheap and efficient imported modules, with modest and delayed improvements in domestic manufacturing (___). By 2018, there was minimal overlap between these two segments; none of the major solar developers, except the Adani Group, had invested in domestic manufacturing. Since the sector was heavily dependent on low-cost imported modules, the import taxes disrupted the balance of incentives, that existed so far and had prioritised solar developers. Developers argued that import taxes "compromised" the country's solar ambitions and risked being counterproductive. Due to tariff caps in auctions, developers were unable to increase tariffs to offset the higher costs from import taxes, leaving them vulnerable to reduced profitability – a concern which amplified with negative experiences with DISCOMs in different parts of the country. ____

Annual capacity additions start decelerating in 2019, a trend further intensified by commissioning delays caused by COVID-19 lockdowns in 2020. A period of persistent under-subscription in solar auctions also began in 2018 and extended until 2022. A phenomenon owed to increased costs from the dual effect of import duty and supply chain constraints.

3.3.5. Stabilisation of growth (2021 – 2024)

The impact of barriers and conflicting pressures resulted in a brief slowdown in technology growth. However, the policies implemented around 2017 helped prevent a prolonged downturn, especially with central-led auctions pulling up capacity additions. Nevertheless, continuous acceleration of technology growth couldn't be sustained. As a result, since 2019, solar technology entered a stable growth phase nationally – a phase marked by the continuous balancing of drivers and barriers. That said, regional dynamics in technology growth altered. Unlike in the acceleration phase, in 2021, we observe renewed acceleration in capacity additions led by north-western states (particularly RA and GU), which added nearly three times the capacity of their southern counterparts. While solar technology grew rapidly in this region, there is a cessation of past growth patterns observed in the south. In 3 of the 4 leading states (KA, AP and TE) capacity addition does not bounce back to pre-covid levels. That said, we observe a continued expansion in TN and an acceleration of growth in MH after years of stagnation. In TN, capacity addition is led by non-state auctions with state discoms' failure to conduct successful ones. In recent years auctions in TN have remained largely undersubscribed. In contrast, discoms in MH (one of the few states), have persisted in conducting auctions despite initial periods of undersubscriptions. These are especially tied to agri-feeder KUSUM scheme.

Cost and tariff trends followed similar patterns to the previous period. In addition to import duties, module prices rose due to increased freight costs from COVID-19-related delays and a surge in polysilicon prices caused by supply shortages from early 2021 to mid-2022. This combination of factors led to an increase in LCOE and capex from 2022 (IRENA 2024). Despite these cost pressures, the industry demonstrated resilience with no significant changes in annual capacity additions or auctioned. The capacity auctioned by central off-takers dropped sharply in 2022 and 2023, largely due to delays in finalizing RPOs and clearing backlogs of power sale agreements with state DISCOMs. Meanwhile, from 2023, state-led auctions saw a significant uptick, primarily driven by the DISCOMs in GU, RA and MH.

In this phase, the density of the active policy mix doubles with the largest policy addition in absolute terms. Policy making logics are driven by the need to integrate solar more deeply into both the physical and operational aspects of the existing energy system. To support system integration, policies targeted several key barriers, including the persistent issue of delayed payments by DISCOMs, rising instances of curtailment, and challenges with open access regulations—particularly for captive consumption, wheeling, and banking—at both the national and state levels. In terms of complementary technologies and infrastructure, policies aimed at mitigating the challenges of intermittency with a stronger focus on energy storage solutions. Grid limitations were also addressed through policies promoting the development of transmission infrastructure and setting up auctions to do so.

While new policy priorities and instruments emerged, existing ones remained in place. Policies supporting domestic manufacturing and market creation continued alongside newer initiatives. Recent market creation policies nationally were linked to targets for setting up specific capacity or generation, regulations tied to addressing barriers related to commissioning delays caused by covid and issuance of auction guidelines when solar is tied with storage. At the state level, these policies addressed barriers related to state's non-fulfilment of RPOs. Additionally, for the first time, policies aimed at phasing down incumbent fossil-fuel-based technologies were introduced. These included market-based economic instruments, such as the authorisation of a carbon credit trading scheme, and capacity-based target setting instruments, with plans to replace 30 GW of thermal capacity with renewable energy by 2025-26.

Policy-making logics during this phase were primarily driven by technology-specific objectives, while nonetheless receiving strong political support from an unchanged political regime. This was demonstrated at COP26 in 2021 where India announced ambitious 2030 targets to reach 500 GW of renewable energy capacity, with nearly 300 GW expected to come from solar. Additionally, India also committed to achieving net-zero emissions by 2070. With that, we also observe the continued effect of international climate policy trends. Specifically, the authorisation of a carbon credit trading system in India reflects a response to EU's Carbon Border Adjustment Mechanism (CBAM) set to commence from 2026. It is expected to affect India's significant exports of energy-intensive goods like aluminium, iron, and steel to the EU. The carbon trading scheme was approved in 2023 and is expected to become operational by late 2025 or 2026. Although primarily driven by broader climate goals, this is likely to benefit solar technology growth, although the extent of this effect is yet to be known.

Table 2: National technology developments and evolution of policy making logics, political contexts and external events

Time period	Technology growth phase	Technology cost and tariffs	Technology-specific policy making logics	External events and political context	Policy density and share of priorities nationally at the end of the period
~ 2009	Formative Take-off in 0/18 states	Very high costs. Compensations based on FiTs	Technology-specific policies in 1-2 states. New policies aimed at developing a framework for supporting and integrating renewable technologies in the power mix.	Ongoing power-sector liberalisation. Solar emerges as part of India's contribution to global climate action.	6 C: 8% M: 0% S: 92% N: 0% L: 0% O: 0%
2010 - 2013	Formative Take-off in 4/18 states	High costs and tariffs but both rapidly declining Start of auctions.	First technology-specific policy adoption nationally and increased policy diffusion at the state-level. New policies are layered into existing frameworks without disrupting, rather supporting current regimes to engage.	Leader states emerge driven by favourable conditions giving rise to a political entrepreneur.	12 C: 19% M: 6% S: 73% N: 0% L: 2% O: 0%
2014 - 2018	Accelerating Take off in 13/18 states	Rapid decline in costs and tariffs. First auction tariff and cost below wholesale electricity price.	New policies target protecting interest of key actors involved in technology growth along with creating synergies with existing complementary technologies.	The political entrepreneur assumes power nationally, leading to a regime shift and rise of a new coalition of interests and ideologies. WTO rules against India wrt. LCR in solar auctions.	38 C: 21% M: 19% S: 50% N: 7% L: 3% O: 0%
2019 - 2020	Stable Take off in 14/18 states.	Slow down in decline in costs and tariffs.	New policies follow established trajectories while incorporating COVID responses. However, contradictory tensions arise within the policy mix.	Covid pandemic caused national lockdowns and delays in project commissioning.	63 C: 24% M: 28% S: 37% N: 8% L: 2% O: 2%
2021 - April 2024	Stable Take off in 15/18 states.	Very little decline in costs and tariffs.	New policies offer increased support towards developing complementary technologies and infrastructure and removing barriers towards greater system integration. For the first time, policies aim at phasing down incumbent technologies are introduced.	Supply chain disruptions emerge not only as a post-pandemic phenomenon but also due to global demand-supply imbalances for raw materials.	121 C: 18% M: 24% S: 40% N: 17% L: 1% O: 0%

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