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Review

India's state-led electricity transition: A review of techno-economic, socio-technical and political perspectives

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ABSTRACT

India's electricity sector is in the midst of a transition that will have immense consequences for its own development and for global decarbonisation efforts. Sustainability transitions scholars have highlighted the importance of integrating insights from multiple disciplinary perspectives to holistically understand national energy transitions. This search-based narrative review assesses the academic and policy literature on India's electricity sector transition from January 2011 to October 2022 and synthesizes it along three broad perspectives identified by Cherp et al. - techno-economic, political, socio-technical – and a fourth cross-cutting perspective 'justice'. It finds that India's electricity transition is state-led, with the state modulating the pace of the transition through its pro-renewables policies and its control over energy resources, assets and incumbents. India's national innovation systems is weak, leaving the state in-charge of stimulating transitions in line with its developmental objectives. While the policy-mix has successfully driven renewable energy deployment, it has been unable to stimulate manufacturing. A complete shift away from coal is likely to take multiple decades due to a young thermal fleet, multi-layered political lock-ins beyond jobs, demand-side uncertainties, and practical challenges with grid integration. Finally, it identifies six cross-cutting research gaps relating to (1) the role of the state (2) incumbents and non-state actors (3) green industrial policy (4) core political constituencies and institutional systems (5) economic diversification and social protection and (6) India's development pathway.

1. Introduction

India is home to one-sixth of humanity and is projected to witness the largest energy demand growth of any country over the 2020–40 period [1]. It's electricity demand growth is tied to its GDP growth, urbanization, expanding irrigation needs and growing air-conditioning demands [2–7]. To meet this growing demand, India is poised to add a power system the size of the European Union over the next two decades. India's electricity transition is significant due to its aspirations of becoming a global hub for green technology production and its potential for exemplifying an unprecedented low-carbon development pathway.

Emblematic of India's electricity transition is its national target of achieving 500GW of non-fossil electricity capacity by 2030 [8] and its global commitment to achieve net-zero by 2070 [9]. However, a focus on energy capacity and emissions only captures a part of India's transition story. Apart from a shift from fossil-based to clean power generation, India is experiencing multiple simultaneous transitions, such as: a shift from public to private control over energy infrastructure; growing per capita energy demand; expanding domestic power markets; and transitions in coupled sectors such as transport and industry [2,10]. Understanding India's electricity transition in all its complexity is thus an urgent and policy-relevant task.

An emergent global literature dedicated to understanding sustainability transitions offers useful frameworks for this. This literature suggests that transitions are multi-dimensional, multi-actor processes entailing co-evolutionary change [11–13]. Stocktakes of transitions research have asserted that no single discipline can capture and describe a transition exhaustively [14,15]. Sustainability transitions research thus requires harnessing and inter-relating knowledge from different disciplines [16]. Indeed, the sustainability transitions knowledge base is becoming increasingly multi-disciplinary, drawing ideas from geography, political science, sociology, business administration, and several other disciplines [13,15,17,18]. Suitably applied, analytical and methodological insights from the broader sustainability transitions literature can help shed light on national electricity transitions.

Combining insights from multiple disciplines to create a holistic picture of a national energy transition is easier said than done, given the differences in the ontological and epistemic basis of these disciplines.

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Several authors have attempted to produce meta-theoretical frameworks that provide ways to do this in a coherent and structured manner (see Table 3 of [16]). One such meta-theoretical framework was proposed by Cherp et al. [16], specifically tailored to analysing national energy transitions. They conceptualize national energy transitions as a co-evolution of three prominent *systems* - energy flows and markets, energy technologies, and political actions and policies. The theoretical knowledge concerned with each of these systems corresponds to three broad scholarly 'perspectives', respectively - techno-economic, socio-technical and political.

- *Techno-economic perspectives* are rooted in economic history, neo-classical economics, and energy systems analyses; IAMs are an example application of this perspective.
- *Socio-technical perspectives* are rooted in STS, sociology of technology and evolutionary economics.
- *Political perspectives* stem from political science, international relations and policy studies.

These three perspectives have varying relative strengths in explaining particular aspects of the transition, and taken collectively, they help paint a holistic picture of national transitions. However, these three perspectives are not exhaustive or complete. Sovacool et al. [19] discuss three other epistemic communities that bring unique perspectives on energy transitions; these are concerned with energy justice, social practices and the responsible innovation.

I include the justice community's perspective in this review due to the relevance ascribed to justice questions in global policy discourses and in agenda setting pieces from the field of sustainability transitions [11,20]. This perspective differs from the previous three perspectives in that its focus is not necessarily on the 'systems' that constitute a national energy transition. Rather, this perspective is honed in on the needs of individuals. In this sense, justice concerns intersect with at least the political and socio-technical perspectives. Scholars coming from this perspective focus on how costs and benefits of the transition are distributed, due process, and the fair recognition of marginalized groups.

- *Justice perspectives* are grounded in moral studies, ethics and political science.

The objective of this review article is to organize and synthesize literature from multiple disciplines on India's electricity transition. As argued above, no single discipline can holistically capture the various dimensions of national electricity transition; thus, reviewing insights from multiple disciplines would allow readers to get a holistic (but not comprehensive) view of India's transition. Rather than present deep dives into deeply nuanced thematic area, this paper adds value through its broad scope. This allows me to derive integrative and synthetic insights on India's electricity transition in the discussion, and identify cross-cutting research gaps.

I present the findings in the form of an accessible, if slightly superficial, narrative making this review especially useful for energy generalists and non-India specialists, in keeping with the journal's objectives. Further, disciplinary scholars and experts in particular fields within transitions research may find it useful to see their views and their work contextualized alongside work from other disciplines, facilitating reflexive thinking. It can also serve as an encyclopaedic reference for scholars already familiar with India's energy sector. The discussion and research gaps sections are where I move from synthesizing literature to substantively offering original comment and arguments.

Rather than proposing an original schema for categorization, I use these four theoretical perspectives discussed above as the organizing principle for this review, for two reasons. First, the three perspectives from Cherp et al. correspond to distinct systemic foci, theories, and disciplinary roots (see Table 2 in [16]), making them less arbitrary as an organizing principle. Second, since the literature on transitions is growing rapidly, this approach has the potential to become a long-lasting and robust review framework. Future reviews of India's electricity transition literature could build upon these same categories, rather than starting afresh.

The novelty of this review also needs justification given that several studies discussing India's electricity transition already exist. Existing review studies are often focused on particular dimensions of the transition – for instance, specific technologies [21–31], policies [32–35], or places [36–38]. Choosing a (relatively) narrow scope allows these studies to present the dynamics of India's electricity transition in depth. This review builds upon several of these studies. Additionally, none of the comparable studies [39–44] use a such a broad query-based search. The academic and policy literatures on India's electricity transition largely exist in silos, with limited cross-pollination of insights. I attempt to combine insights from the two, which adds to the novelty of this review.

Section 2 discusses the methods used, laying out the scope of the paper and its limitations. Section 3 presents the main findings in a narrative synthesis. Table 2 highlights some of the key findings. Section 4 is a discussion section, which reflects upon the findings from Section 3 and presents cross-cutting insights by discussing three overarching questions about India's transition. Section 5 highlights a few research gaps stemming from the findings, and discusses ways to approach those gaps. Section 6 concludes by reiterating the contributions of this paper and calls for a co-produced research agenda.

2. Methods

This study is a qualitative narrative review, based on search criteria, explicit parameters and a sample [45]. It primarily draws on journal articles, book chapters and policy reports, but in a few instances uses news pieces and data dashboards for capturing recent developments and standardized time-series data. The period chosen for review is Jan 2011 to October 2022, since 2010 is considered a turning point in India's RE story due to significant policy changes following the launch of India's 2008 National Action Plan on Climate Change (NAPCC). The scope of this paper is limited to India's coal-to-renewables electricity transition, with supplemental attention to the closely-linked issue of a just transition in coal regions. The focus of this paper on India's electricity transition, not its energy transition. Thus, energy applications such as cooking are beyond the scope.

The search strategy followed a three-pronged approach (Table 1):

1. An initial scoping study helped gauge the size of the literature, and inductively improve the search query. Subsequently, the main query-based search was conducted in July 2020 to identify academic articles from January 2011 to July 2020, using the Web of Science database, which yielded 9980 records. These were manually screened for relevance by title, and then by abstract, to yield 326 results. These were read and a selection was included in the final draft based on the relevance to the scope, the rigor of the evidence assessed, and as per the inclusion criteria described below. Since this is a fast-moving topic and given the time it took to review the articles, a second search using the same query was conducted to update the review till mid-October 2022, which resulted in 5996 records which were similarly shortlisted.
2. Policy reports were reviewed over the same period. A substantial portion of the most relevant research in India is circulated as grey literature. These were identified through thematic google searches and by scouring websites of policy research groups.

Table 1
Search terms used for finding academic articles from the Web of Science platform.

Component 1 - India related terms	Component 2 - electricity/energy related terms	Component 3 – transition related terms
India OR Indian OR Andhra Pradesh OR Arunachal Pradesh OR Assam OR Bihar OR Chhattisgarh OR Goa OR Gujarat OR Haryana OR Himachal Pradesh OR Jharkhand OR Karnataka OR Kerala OR Madhya Pradesh OR Maharashtra OR Manipur OR Meghalaya OR Mizoram OR Nagaland OR Odisha OR Punjab OR Rajasthan OR Sikkim OR Tamil Nadu OR Telangana OR Tripura OR Uttar Pradesh OR Uttarakhand OR West Bengal OR Chandigarh OR Delhi OR Daman OR Diu OR Andaman OR Nicobar OR Lakshadweep OR Dadra OR Puducherry Or Pondicherry OR Chandigarh	"energy" OR "electricity" OR "electric" OR renewable$ OR "green" OR "power" OR "wind" OR "solar" OR "PV" OR "hydropower" OR "biomass" OR "storage" OR batter* OR "sustainable" OR "sustainability" OR "coal" OR "thermal" OR "power" OR "powerplant" OR "demand" OR "socio-technical" OR "socio-ecological" OR "discom" OR "distribution" OR "utility" OR "grid" OR decentral*	"transition*" OR "transformation$" OR "decarboniz*" OR "phase out" OR "disruption" OR "disruptive" OR "innovat*" OR "deployment" OR "future" OR "capacity" OR "target" OR "disseminat*"

The search query was comprised of three components containing related terms separated by OR operators, while the components themselves were connected by AND operators. Additional filters:
LANGUAGE: (English) AND DOCUMENT TYPES: (Article)
Indexes = SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI
Note: The regions of 'Ladakh', 'Jammu' and 'Kashmir' were excluded from the search query due to an oversight. This was identified during the review process, but it was not possible to update the search.

3. Additional records were inductively discovered by following bibliographic citations and by using a bibliographic graphing tool based on the Semantic Scholar Paper Corpus.[1]

In terms of the inclusion criteria, this implies a focus on three key technologies (solar PV, on-shore wind, coal). Papers discussing the energy transition or renewable energy (RE) in aggregate terms were included. In terms of disciplinary scope, the inclusion criteria are much broader. I included social science papers that correspond to the four perspectives identified in Section 1. Cross-country comparative or multi-country studies were also included if India was mentioned as one of the countries assessed in the abstract or keywords.

Technical and engineering related papers, as well as most environmental economics papers were excluded. Papers narrowly focused on other forms of renewable energy such as solar thermal, offshore wind, bioenergy and small hydro were excluded, since modelling indicates that these technologies would play a marginal role in the future energy mix. Other sources of conventional energy such as oil, gas, large hydro and nuclear were excluded for the same reason. Studies discussing the general functioning of the power sector or electricity distribution reform were generally excluded, with a few exceptions that highlight key barriers to the transition rooted in the sector's legacy issues. Cross-cutting themes such as India's agricultural electricity transition [46–49], air pollution and electricity transition [50,51] or COVID impacts on India's transition [52–55] are also beyond the scope as defined, but may be important for understanding linkages between electricity transitions and sustainable development. Papers primarily about India's climate policy or the energy efficiency space were excluded from the review unless they focused on India's energy-related targets.

A limitation of this review is that organizing the findings along thematic areas into a flattened narrative risks missing key temporal evolutions within the literature. This article does not offer bibliographic insights to keep the papers scope tractable.[2] Since the sampling is limited to English-language journals and grey literature, the review risks privileging formal academic and policy knowledge over experiential and practical insights. Finally, the search-based component of the review relies on one only academic database - the Web of Science. A more comprehensive search could include other databases, such as Scopus.

3. Findings

This section presents the main findings in narrative form, organized around techno-economic, political, socio-technical and justice perspectives. The sections are disaggregated into thematic sub-sections, but this is done only for greater readability and narrative flow. Boundaries between sub-sections are highly fungible, and many cited works could fall under multiple sub-categories. Table 2 summarizes the findings while highlighting themes covered under each perspective.

3.1. Techno-economic perspectives

3.1.1. Changing electricity mix – trends and scenarios

The 2011–20 decade witnessed a near doubling of India's electricity capacity (Fig. 2) [59]. The capacity mix has started shifting in favour of renewables, but in absolute terms, new RE is layering upon an expanding thermal fleet. Both RE and coal capacity doubled in the first half of the decade, as policymakers pursued aggressive capacity addition in response to high GDP growth in the late 2000s. This and demand overestimation resulted in a capacity 'surplus' around 2015 [60]. Since then, RE - especially solar - has maintained its exponential growth while coal capacity additions slowed down.

The generation mix has changed only at the margins thus far (Fig. 3). Notably, RE's gains in generation have come at the cost of natural gas, and not coal. Thermal power (mostly coal) continues to be the bedrock of India's power system.

National policies and plans indicate that policymakers and energy planners, such as India's Central Electricity Authority, are driving this change. In its 2022 NDC update, India committed to achieving 50 % cumulative installed power capacity from non-fossil sources by 2030 [64]. As shown in Table 3, this would imply that the share of coal in the generation mix would reduce by a third even as absolute capacity expands.

Drawing directional insights about India's future energy mix from independent scenario studies [2,67–95] is challenging due to the large divergence in estimates [96,97]. Structural uncertainties associated with India's development pathway, such as the GDP growth rates, economic structure and urban form drive scenario divergence, even more so than climate and energy policy assumptions [96–98]. Recent modelling studies include a few pathways that are potentially consistent with 2070 net-zero for India, however many of these rely on aggressive decarbonisation post-2050 [97]. These pathways typically include reductions in coal-fired capacity in the next decade or early penetration of coal-CCS, significant fuel-switching, service demand reduction, and modal shifts in transport [97]. Very few scenario studies showcase faster transition pathways that reach net-zero before 2070 (e.g. [81,82,93,99]).

Current cost and ownership trends suggest that most future

[1] https://www.connectedpapers.com

[2] See Debnath et al. [56], Goyal [57] or Haldar et al. [39] for bibliographic insights on India's energy transition.

Table 2
Summary of key insights on India's electricity transition, organized by theoretical perspective and theme.

Perspective	Themes	Insights
Techno-economic	Changing energy mix – trends and scenarios	• Privately-owned, utility-scale RE accounts for most recent greenfield capacity additions • Coal's share of generation has remained unchanged over the last decade. It is anticipated to drop by 1/3rd this decade. • RE's gains in generation have come at the cost of natural gas, and not coal. • Modelling studies diverge significantly, with developmental decisions rather than policy being the key driver • Both thermal and RE capacity doubled in the first half of the 2010s, but RE has maintained its exponential growth since then while thermal growth has slowed down substantially
	Future of thermal power	• Some analysts argue that India is transitioning towards even greater use of coal • Economic case for thermal electricity is weakening • Significant demand uncertainties and asset lock-ins to coal have resulted in India adopting a clean coal strategy • The average age of the thermal fleet is just 12 years • A viable model for accelerated retirements of thermal plants has not yet been developed
	Grid integration	• Grid integration is feasible in principle and at low economic costs • High RE capacity additions may not avert need for new coal capacity, unless storage increases dramatically • Flexibility studies suggest adopting state-specific portfolio of options and managing inter-state disparities
Political	Electricity political economy	• Transition drivers included energy sovereignty, attracting investments, global pressures; environmental concerns played a secondary, but not insignificant role • Sub-national political economies of the power sector, particularly the distribution sector, greatly shape India's transition • Barriers include financial health of utilities, financial resources and contextual institutional weaknesses • Federal dynamics strongly shape transition governance Individual change agents played an outsized role in stimulating change • Policymakers leveraged market forces to bridge capacity gaps, creating fragmented governance
	Coal political economy	• Coal's developmental contributions are high and political roots are deep, extend far beyond jobs • Coal's contributions to public finance and railways are salient lock-ins • Coal labour regimes are highly varied, with a large number of informal and indirect jobs in some districts
	Policy instruments and mix	• Feed-in tariffs, RPOs, reverse auctions and solar parks are some important instruments in the RE policy mix • Policymakers have attempted to create an efficient, competitive, liberalized sector, but only partially succeeded • An incoherent policy mix resulted in deployment at the cost of domestic manufacturing; recent policies strongly focus on manufacturing
Socio-technical		• India's national innovation system is weak and underfunded • The state modulates multi-level change in the absence of bottom-up innovation pressures • Regime resistance - bureaucratic and corporate - is linked to inertia; incumbents [58] also stimulate niches and are diversifying into RE • Technology diffusion helped particular firms become competitive globally, but has not stimulated broad innovation capabilities in India's NIS • Several micro-level studies exist that evaluate social aspects of distributed RE, but insights from these are fragmented
Justice	Energy justice	• Patterns of injustice are being reproduced in India's emerging RE infrastructure, particularly around land issues • Scholars have called out the scalar bias in India's solar trajectory
	Just transition	• The 'just transition' frame has discursive power in India, but the concept is still evolving • Feasibility of replacing coal jobs with green jobs appears to be low • The clean energy transition is unlikely to cause coal job loss in the near-to-mid term

greenfield capacity is likely to manifest as privately-owned, utility-scale, grid connected solar and wind projects [100]. Whereas thermal ownership is spread evenly across Central, state-level and private generators, renewables' ownership is overwhelmingly private [101].

3.1.2. *The future of thermal power*

The economic case for coal-based thermal power is already weakening [102]. The unit cost of new RE has fallen to INR2–3/kWh (varying by tender), and is now lower than most new and some existing coal plants [100,103,104].[3] Accounting for environmental costs excluding climate impacts, new RE had already become cheaper than nearly all thermal plants in 2018–19 [102]. Lower than expected demand growth has led to low capacity utilization of thermal plants, increased ramping-related wear and tear, and escalating operating costs [56,60]. Recently commissioned thermal assets have struggled to secure long-term fuel supply and power purchase agreements [105,106]. A Parliamentary standing committee report identified 30+ thermal plants as stressed or stranded in 2018 [105]. Currently proposed coal plants also risk becoming stranded assets as RE costs drop and if climate policy stringency increases [106,107]. Currently, 210GW of coal-based thermal capacity is estimated to be in the pipeline; although only 27GW is under construction and poised to be commissioned [61].[4]

Even as the economics of thermal power are weakening, a series of asset lock-ins and substantial demand-related uncertainties ensure its perpetuation. The average age of India's coal fleet is just 12 years [107]. The 'take-or-pay' structure of long-term power purchase contracts secured by existing assets leave state-backed distribution utilities on the hook for paying fixed costs regardless of offtake [108]. On the demand

[3] Whether this proposition holds while including RE subsidies and balancing costs is contested

[4] All of which are public projects

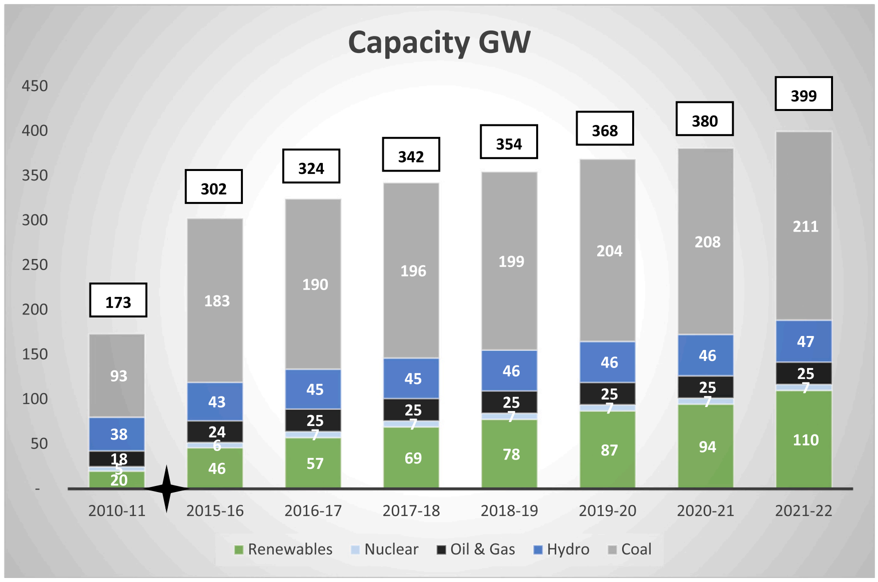

Fig. 2. Installed electricity capacity by source. The numbers in boxes represent sum totals. Source: [61]. Renewables data for 2010–11 from [62]. Renewables include solar, wind, biopower and small hydro.

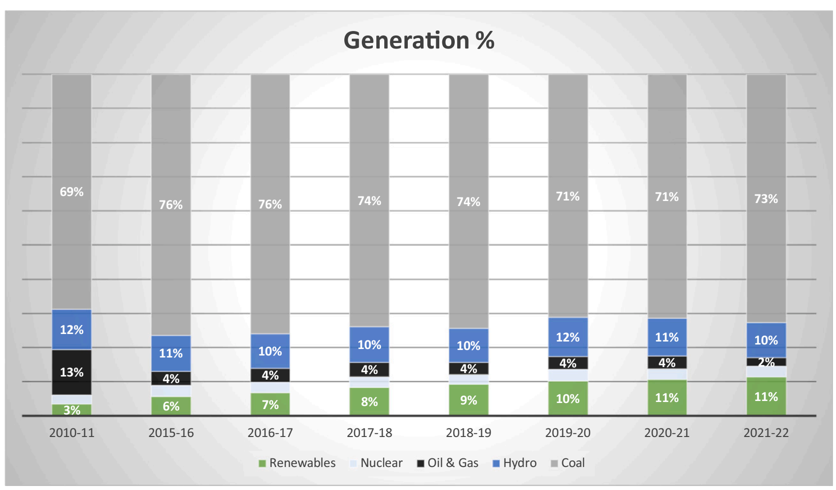

Fig. 3. Shares of India's power generation mix by source. Source: [61]. Data for 2010–11 from [63].

Table 3
India's future power generation mix as projected by Union governmental planning bodies.

Scenario/study	Installed capacity GW				Capacity share %			Generation share %		
	Coal	Solar	Wind	Total	Coal	Solar	Wind	Coal	Solar	Wind
Actual energy mix at the end of 2021–22	211	54	40	400	53	14	10	73	5	5
CEA report on optimal mix for 2029–30 [65]	267	280	140	817	33	34	17	54	19	12
CEA National Electricity Plan (Draft) for 2031–32 - *base case* [66]	249	333	134	866	29	39	16	50	23	12

side, widely-varying scenario studies and the political aspirations for high-GDP growth represent significant uncertainties [96–98], resulting in a conservative policy approach to energy sufficiency. Scaling up alternative baseload sources such as nuclear has proved challenging, providing further incentives for the continuation of thermal power [103,104,109–111].

These lock-ins, in addition to coal's political lock-ins (Section 3.2), have manifested in the form of a protective impulse towards thermal power among policymakers. The government has undertaken several measures to enhance the value proposition of thermal power, such as mandating supercritical and ultrasupercritical technology [112,113], importing higher grade coal, targeting 100MT coal gasification by 2030, and promoting coal washing and plant modernization [103,114–116]. This has been accompanied by reforms aimed at strengthening the economic fundamentals of the coal sector such as streamlining coal allocation and introducing commercial mining [117]. Given these efforts, emission intensity from grid connected powerplants is projected to halve by 2026–27 from 2005 levels [114,118]. Yet, India's 'clean coal' strategy is not fully credible. In the absence of fundamental market reforms, efficient plants continue to be under-utilized in favour of older, inefficient plants due to their lower fixed costs and cheaper coal supply linkages [119].

Given India's young thermal fleet, reducing the average lifetime of thermal powerplants is expected to be the most important decarbonisation lever for the coal sector [120]. A few studies have estimated substantial economic benefits from accelerated retirement of old, inefficient plants [56,119–124] and identified candidate assets. Others proposed levers include targeting super-polluting plants for retirement [125,126], imposing a 'coal moratorium' [107,127], repurposing [128,129], and securitizing thermal assets [124]. However, a viable model for accelerating coal retirements has not yet been developed at either the national or the sub-national level. There is active contestation over the criteria for identifying candidates for retirement or repurposing [119,125,127]. For instance, using age-based criteria may cause second order effects, such as the realization of in-the-pipeline capacity which may not have otherwise materialized. Further, states with multiple polluting assets are likely to be averse to surrendering too much capacity [119].

3.1.3. Grid integration

The future of coal is intimately tied to the penetration of renewables in the energy mix. Most of India's RE capacity is grid interactive rather than off-grid RE, thereby making the penetration of renewables contingent upon successfully achieving 'grid integration' i.e. power system practices that collectively enable the efficient and reliable connection of variable RE.

While the profiles (correlation, smoothing, seasonality) of onshore wind and solar are generally complementary in many parts of India [130–134], the concentration of these resources is low in the Eastern and North Eastern parts of the country, the regions that possess the most coal [135].

Modelling studies concur that grid integration in line with India's 2022 [136,137][5] and 2030 [135,138,139] RE targets is feasible in principle, and at relatively low additional costs. One set of studies [140,141] found that complementing India's 2030 target of 500GW RE with 252GWh of grid-scale battery storage and shifting ~50GW agricultural load to daytime could be the least-cost integration pathway, assuming storage costs fall 30–40 %. Studies exploring grid integration technologies suggest that India should adopt state-specific portfolios of flexibility options, evolving over time [94,133,138,142–147]. Retrofitting thermal plants for flexibility, augmenting transmission infrastructure and exploiting dispatchable hydro and pumped hydro storage are some options that are available immediately. Modelling results also indicate that high RE capacity addition will not necessarily avert the need for new fossil capacity due to India's peak demand patterns; however, a balanced solar-wind portfolio could reduce thermal utilization and flatten electricity emissions [140,148]. This implies that minimizing India's fossil infrastructure will require rapid wind additions, not just solar.

Integration is proving to be challenging in practice, however, due to institutional weaknesses of the power sector – nascent power markets, weak tariff signals, inadequate data and capacity for RE forecasting. Many states and regions are already facing integration issues within their administrative limits, and RE curtailments have increased [135]. Eliciting the requisite investments for retrofitting coal plants, an important short run flexibility option, has also proved challenging [135,149].

3.2. Political perspectives

3.2.1. Electricity political economy and governance

At the national level, India's embrace of RE has been driven by energy sovereignty, the prospects of attracting investments, global pressures to decarbonize, and the desire of political leaders to brand themselves as green modernizers [150–154]. Environmental pressures and climate mitigation have notably not been primary drivers, but neither are they insignificant. The literature does not report demand from citizens or power consumers as being influential factors in favour of RE.

The political economy of India's electricity sector is locked-in to a low-level equilibrium as a result of incomplete liberalization, politically-charged management practices such as widespread tariff subsidies, clientelism, weak regulatory autonomy, and other institutional design issues [155–159]. The failure of independent electricity sector regulators to appropriately govern, as demonstrated by the accumulating losses on utility balance sheets, irregular tariff revisions, inadequate consumer protections, and delayed enforcement of orders [160–162], is a legacy malaise of the sector that is likely to influence India's transition governance going forward. These legacy governance issues are particularly concentrated in the distribution sector, leading to poor outcomes such as low collection rates, electricity theft, stranded and non-performing assets, high losses, and crippling debt [155,163].

India's electricity sector falls under the joint jurisdiction of the national government and state governments. Recent scholarship has identified the state-level as the key arena for analysing political economy dynamics, and has strongly advocated context-specific approaches to electricity reform [156–158,164–166]. This literature has sometimes advanced reform ideas akin to the political settlements approach [167,168], in contrast with the prevailing reform wisdom that includes the remedies of privatization, unbundling and corporatization. Limited fiscal space in Indian states often results in delayed subsidy disbursement and the non-payment of electricity dues by government departments. This strains utilities' ability to make grid improvements, which intensifies renewable integration challenges. The conceptualization of electricity as a welfare good rather than as a commodity has resulted in a progressive tariff structure, whereby commercial and industrial consumers cross-subsidize agricultural consumption [10]. This tilted structure disincentivizes distribution utilities – likely the most important actors in the ecosystem – from facilitating decentralized RE for the fear of losing their most remunerative customers [169]. By the same logic, utility incentives are stacked against allowing rooftop solar penetration [10,169–172].

This federal institutional structure is arguably the most important governance factors for its transition [173]. While the national level is responsible for policy-making and target setting, the states undertake both policy-making *and* implementation. On the one hand, this allows states to function as laboratories for policy experiments [174], which then diffuse horizontally and vertically. For instance, progressive regulators in Maharashtra "drew up a seminal order for feed-in tariffs that became one of the cornerstone instruments of the wind industry" [150]. On the other hand, governance at the national level is constrained by what can be implemented sub-nationally [152,175–178]. The national government has usually taken the lead in setting long-term RE targets, partly because states have tended to lack the mandate or the capacity for long-term visioning related to the energy transition. This has manifested in the top-down devolution of RE purchase obligations to which most states have responded in a piecemeal and belated manner, resulting in a dynamic where the national government has needed to cajole states to increase their ambition [179]. For instance, when RE tariffs were high, states did little to encourage private investors, instead placing the onus of land acquisition and building interconnection infrastructure on developers and constraining them from selling power outside the state [33]. The reluctance of states to pursue RE can be explained, in part, by their direct exposure to grid integration challenges, varied RE resources, and political preference for job- and rent-creating fossil infrastructure. The success of India's key climate commitments is contingent on improved multi-level governance in the power sector.

Apart from the financial health of state-level utilities, land acquisition issues and the high cost of capital for RE are some major barriers to

[5] India has a target of achieving 175GW of RE by the end of 2022.

the transition [101,152,154,180–185]. Finance costs account for more than half of RE tariffs in India [180].[6] Major factors contributing to high financing costs in the Indian context include inferior debt terms compared to international finance, short tenors and variable interest rates, and high risks perceptions among financiers [186–189]. Risk perceptions themselves are related to institutional weaknesses in the power sector: policy inconsistency across jurisdictions, frequent changes in law, payment delays, attempts to renegotiate contracts, and inadequate performance data [190–192]. Several studies highlight institutional, political and regulatory barriers to transition as pivotal, over technical, economic or behavioural ones [181,184]. In brief, the governance barriers to the electricity transition are deep, multitudinous and are linked with legacy issues of the broader power sector.

To bypass political and administrative lock-ins, policymakers have adopted an approach of grafting the market onto a state-led sector, an approach described as 'market-plus' [155,177,193–195]. This relies on intensive government involvement in eliciting voluntary participation from private actors through price signals and using market structures to unlock political economies. Private interests with diverging priorities are aligned in informal coalitions so as to minimize opposition to state priorities. The need for such an approach stems from a severe lack of state capacity.

Another institutional innovation in the sector has been the emergence of NTPC and Solar Energy Corporation of India (SECI) as "central offtakers", acting as an intermediate power procurers on behalf of credit-risky Discoms [192]. Their large balance sheets and sovereign parentage have helped hedge counterparty risks, making capacity auctioned by them more attractive to developers. As a result, a significant proportion of RE projects sanctioned since 2019 have been mediated by central offtakers [196].

Individual change agents have played an outsized role in India's transition [197]. They have shaped their institutional contexts in novel ways, leading to pockets of functionality where models of change could be demonstrated [198–201]. Leadership by individual politicians, such as then Gujarat Chief Minister Modi [164], and institutional entrepreneurship by small groups of motivated bureaucrats, regulators, and utility managers (for instance, by actively collaborating with a regional industrial association) have contributed to uneven rates of transition across states [173,177,179,198–201].

As RE's role in India's industrialization has grown, a variety of non-state actors have started shaping the policy process. The role of business actors has increased while the roles of climate negotiators, multi-lateral agencies, and environmental NGOs have relatively diminished [150]. International agencies, domestic civil society practitioners, and policy think tanks have played a key role in sustaining the momentum of India's solar off-grid ecosystem [202], although on-grid eventually became the dominant model.

3.2.2. Coal political economy

Politics around coal are multi-faceted, dominated by jobs concerns but encompassing other issues as well. In total, 51 districts in 13 states of India produce coal, but the economic dependence on coal varies widely within these districts [203]. 284 districts (out of 736) have some form of coal dependency and 33 are heavily dependent [204].

Livelihoods are the central form of lock-in to coal, with a complex set of relations linking the two – a high degree of informality, multiple labour regimes, differing degrees of legality of coal work, and forces of change such as mechanization [204–209]. Beyond jobs, coal has deep salience in terms of its discursive role in nation-making ("resource nationalism"), its functional role in facilitating land dispossession from vulnerable communities, its de facto role in underwriting a vast illegal economy around theft and pilfering during transport, and its multiplicative role in terms of providing revenues and state services to poor districts through public-sector mining enterprises [103,114,207,210–215]. The majority of India's 700MT annual coal production is managed by state-owned miner Coal India Limited [103,114], which has deep roots due to its developmentalist history [213]. An estimated half million pensioners depend on the coal industry [204].

Coal freight cross-subsidizes passenger railway fares, accounting for ~44 % of Indian Railways' freight revenues in 2017 [216]. This is a significant axis of lock-in since a large proportion of India's population depends on low passenger fares to access mobility.

India's coal politics could potentially be deepening, with a 'new' geography of lock-in forming around privately-owned coastal thermal powerplants, new ports, and imported coal [217]. This new infrastructure exists in parallel to an 'old' geography based on public sector coal mining and power generation in heartland states, and coal transport by rail. The continued investment in coastal coal infrastructure, with support from existing political and bureaucratic structures, suggests that Indian policymakers see a continued role for coal in India's development. The faultline between the use of imported and domestic coal is as important to India's energy transition as the one between coal and RE. Policymakers have put in place targets and policies for reducing imports [218][7] but the continuation of India's coal imports reflect the power of new transnational commercial regimes, which are transforming India's economic and strategic relations with countries such as Australia [211,219].

3.2.3. Policy instruments and mix

The policy instruments deployed to drive RE in India have evolved as a function of technology maturity and changing policy priorities. The account below is organized as four stylized, policy phases corresponding roughly to the previous four decades (see Fig. 4 for a rough timeline).

3.2.3.1. Capital subsidies and tax incentives to explore alternative energy sources (up until the early 2000s). Early RE policy focused on state-funded demonstration projects and generous tax incentives such as 100 % accelerated depreciation [220–222], which led to a budding wind manufacturing ecosystem. However, these generous incentives induced ill-conceived wind investments chasing tax benefits and the operational performance of several projects was sub-par [150]. In this phase, while the state supported the advent of the wind industry, the demand for wind power was primarily driven by commercial and industrial consumers who wanted an alternative to an unreliable grid.

3.2.3.2. Public procurement and incentives to enhance energy generation (2000s). The 2000s were a decade of rapid economic development for India, and meeting India's growing electricity demand was front-of-mind for policymakers. Pro-market reforms in the electricity sector, part of a broader wave of liberalization, resulted in the introduction of a competing regime: generation-incentivizing feed-in tariffs – determined on a cost-plus basis – in conjunction with demand-creating measures such as top-down renewable purchase obligations (RPOs) on distribution utilities [179,191,223–225].

RPOs, the implementation of which lies at state-level, turned out to be one of the most important demand creation instrument till date. While they did induce greater public procurement of RE power, the evidence shows that states regularly underperformed on their RPO targets. This was predominantly attributable to a lack of enforcement by state regulators, but their non-enforcement itself was a reflection of divergent priorities of the national and sub-national governments [33,226–229]. While the former has tried balancing multiple

[6] Thus far, the major component of falling RE tariffs are equipment-related costs.

[7] https://energy.economictimes.indiatimes.com/news/coal/india-to-reduce-coal-imports-to-zero-shah/77138335

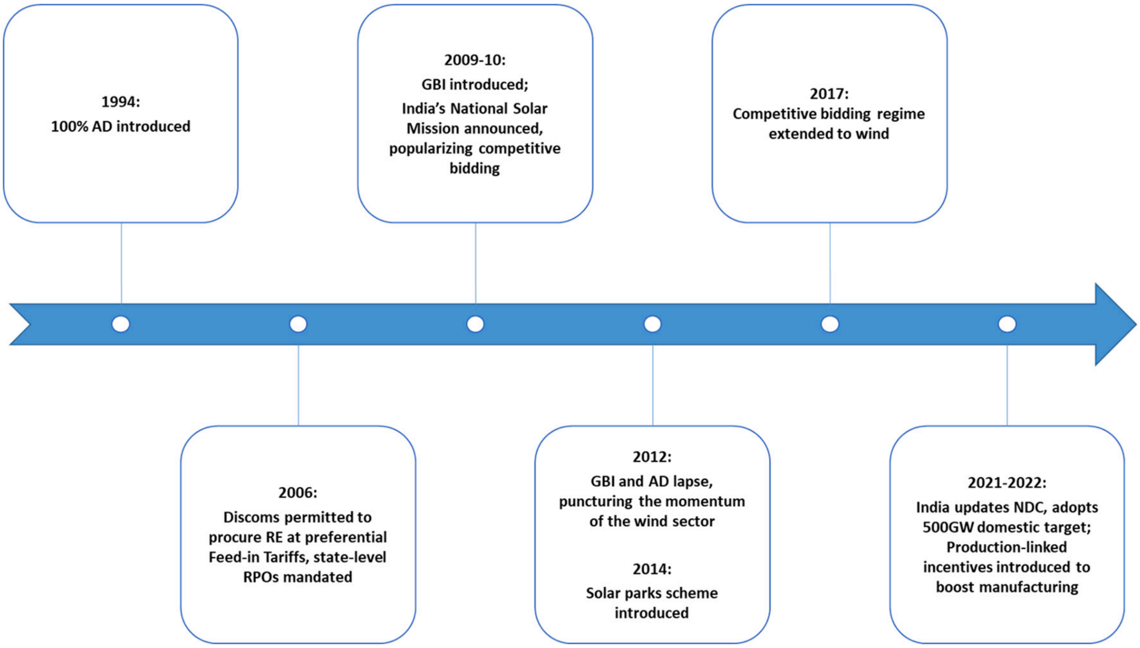

Fig. 4. Key moments in India's RE policy evolution.

developmental objectives (access, security, supply quality, industrial development, decarbonisation) [150,179,230], the latter were much more concerned about the impact of expensive RE power on electricity tariffs, which are hugely important factors in local politics [156].

These policies led to rapid capacity addition in the mid-2000s, but plant performance remained sub-optimal, in response to which a generation-based incentive (GBI) was introduced around 2009. This addition worked well and drew in new players into the wind sector i.e. deployment-focused independent power producers. Their success lead to a paradigm shift away from the monopolistic manufacturer-driven turnkey approach popular within the wind industry, towards a deployment-oriented one [150]. As wind capacity growth exploded, fearing rent-seeking and rising policy costs, policymakers rolled back tax incentives and GBIs before quickly reinstating them, but this flip-flop landed a significant blow to the growing wind industry.

3.2.3.3. Reverse auctions and solar parks for a competitive, efficient, low-cost and clean RE sector (2010s). The launch of India's National Solar Mission (NSM) in 2010, under the NAPCC [231–235], kick-started the solar sector, which at that point had only a few domestic manufacturers operating. The NSM proposed ambitious deployment targets and popularized a competitive reverse auction-based regime, significant domestic content requirements (DCRs), among other measures. For de-risking investments, the NSM pioneered an intermediary procurement model, whereby Central agencies bridged the gap between auction prices and the prices utilities could afford to pay [33,180,231,234,235]. These policies invited in private players who perceived a lowering of the entry barrier and some large bidders who combined their project execution capabilities with cheap technology imports to lodge aggressive bids; the overall result was a rapid decline in wholesale solar prices [223,234,236–238]. The auctions regime was extended to wind in 2017, and brought down wholesale wind tariffs rapidly [33,180].

More recently, the limits of the reverse auction regime have come into focus. The legacy failure of industrial policy in India and the success of its broader economic liberalization had resulted in an ideological preference for minimizing policy costs, and competition was seen as the preferred route to driving down tariffs. Policymakers opted for aggressive rent management to create an efficient sector, with auctions as their instrument of choice [33,186,220,223,231,239,240]. They only partially succeeded in their goals. While auctions did induce aggressive bids from developers, they failed to provide a stable price signal to induce reliable demand for RE from states [33]. Witnessing rapidly falling bids, some states attempted to renegotiate contracts they had signed just a few years prior [33,241]. Poor coordination between the national and state governments also led to several execution issues, leading to undersubscribed auctions, post-hoc challenges with provisioning evacuation infrastructure, and states scrapping tenders where discovered bids were unsatisfactory [33,242]. Policymakers have now signalled their intent to abandon reverse auctions for wind.

As RE growth was becoming mainstream, policymakers were also putting in place a set of enabling policies such as according "must run" status to RE, centrally funded transmission corridors for green energy, improved payment security mechanisms, waived inter-state transmission charges, and innovative models to overcome land acquisition-related challenges, particularly the 'solar park' model, pioneered in Charanka, Gujarat [33,191,220,243–245]. This model, whereby the government acquires and prepares a large park on which private companies can develop RE capacity for a fee, has been particularly effective since it helped reduce investor risk perceptions and drew in higher quality financiers. It has now become one of the dominant modes of solar capacity addition.

These policies demonstrate that the state continued to play a hands-on role in this phase. The combination of market competition and state infrastructure provision was yielding results.

3.2.3.4. Green industrial policies to capitalize on green manufacturing-led development and for enhancing energy security (2020s):. Since 2020, India has begun pivoting towards becoming energy self-reliant (locally termed '*aatmanirbharta*') while also raising its decarbonisation targets [246]. To stimulate domestic manufacturing, India has launched Production-Linked Incentive (PLI) schemes for high efficiency solar cells and modules, and advanced cell chemistry batteries, along with renewed domestic content requirements for government projects [100,247]. INR24,000 crores (~USD2.9bn) has been allocated from the Union budget for the solar PV PLI scheme [246,248]. Clearly, Indian policymakers are betting on domestic green manufacturing as the route to energy self-reliance.

In addition to protecting India's energy security, the policy rhetoric on green manufacturing has also framed it as the new engine of growth and industrial competitiveness. These substantial developmental objectives are being layered upon pre-existing energy-related policy priorities such as low cost power, access and decarbonisation. The stakes and complexity associated with India's RE policy framework are set to intensify going forward. This review can provide some clues about the prospects of India's RE policy going forward based on its historical performance, although this is also proposed as a forward looking research area (see Section 5.3).

While India's RE policy mixes of the 2000s and 2010s can be considered a success in terms of driving clean energy deployment, they fared poorly in relation to inducing green manufacturing [249]. This wasn't due to inadequate attention to manufacturing in the goals set by the policymakers. Most policy documents in this period espoused both manufacturing and deployment as goals. Rather, studies point towards a 'de facto' emphasis on the deployment of mature RE technologies at the lowest cost over support for indigenous innovation and manufacturing in the design and implementation of policies [239,250,251]. A causal link can be drawn from this empirical reality to the political economy of solar energy in India.

Competition between competing coalitions – a transnational coalition of domestic developers, foreign manufacturers, other mitigation-focused interests lobbying for deployment, and a domestic coalition of manufacturers lobbying for greater protectionism – led to deployment being prioritized over manufacturing [249,252,253]. The coalition in favour of deployment was able to influence policymakers to prioritize their interests over those of the domestic manufacturers. Additionally, policy mistakes in the design of the NSMs import substitution policies[8] allowed developers to circumvent them and import cheap PV panels, delivering a further blow to domestic manufacturers [254]. In response to protestations from solar manufacturers, policymakers experimented with various protectionist policies (DCRs, basic customs duty, anti-dumping policies), with limited success [249,255,256].

This account shows that as the multiple objectives tacked onto energy policy broadened and new interests got involved, the coherence of India's policy mix tended to suffer, resulting in partial policy failure. These are precisely the challenges facing India's RE policymakers going forward, suggesting that successfully meeting all the objectives of its energy policy may prove to be unlikely.

3.3. Socio-technical perspectives

Organized R&D in India is underfunded, with their governance centralized in the public sector (within ministries and departments, and as part of sectoral national missions) and within state-owned enterprises [257–259]. India's Union government self-reported an allocation of ~USD110 million in 2017–18 for clean energy research, a meagre amount relative to its sectoral ambitions, and miniscule in comparison with other large nations [257,258,260]. For context, global public RD&D spending on low-carbon technologies in 2018 was USD23.2 billion [258]. The vast majority of India's energy R&D budget is dedicated towards nuclear and oil and gas exploration, in pursuit of reducing import dependence [259,260]. With the exception of clean transport, corporate R&D spends have tended to be oriented towards incremental technology advances and product development [258]. Venture capital activity in clean energy remains limited, although it is rising [258]. Private capital has thus far failed to invest seriously in energy innovation in India.

India has pro-actively exposed its domestic markets to foreign competition, but failed to resolve structural weaknesses in its national innovation system [194,235,261]. China's industrial strength in complementary sectors such as semi-conductor manufacturing was a crucial enabler for its RE ecosystem; such complementary strengths are lacking in India. Further, frequent power cuts and finance challenges have resulted in small-scale private investments in manufacturing [220,235]. Despite these weaknesses, India's national innovation system has shown its ability to drive technological change when mobilized effectively, as in the case of India's national energy-efficient lighting program [262,263].

This account, in addition to the account in Section 3.2.1, suggests that policymakers have been unable to provide an adequately enabling environment for RE niches [264–268]. Niche players have often not been offered adequate state protections, and have instead been exposed to the full force of competition with diversifying incumbents [269]. However, perhaps counterintuitively, India's transition has not been hampered by inadequate niche protection. A relatively favourable set of landscape factors and socio-technical regime (i.e. the locus of established practices and associated rules that enable and constrain incumbent actors in relation to existing systems [270]) dynamics have enabled India's electricity transition.

India is a major importer of oil for transportation and coal for power and coking. The IEA estimates that India can save USD 1.4 trillion on energy imports (mostly due to oil) over the 2019–2040 period in its Sustainable Development Scenario [2]. This, as well as India's commitments under the Paris Agreement suggest strong landscape forces in favour of transition. Most regime actors (incumbent ministries, Discoms, thermal generators) are also discursively aligned with India's pro-transition policies. Evidence suggests that some regime actors have deliberately created niches in developmentally important domains, as in the case of promoting off-grid solar for rural electrification [202]. Incumbents are also playing a complementary role to niches by experimenting with business models not pursued by start-ups, rather than imitating or outcompeting start-ups [271].

However, characterizing regime actors only as champions of transition would miss the mark in India. Beyond their fossil fuel interests, regime resistance [270,272] is also seen to result from the inertia within institutional structures and routines. The relative disempowerment of institutions imbued with the primary responsibility for clean energy diffusion (such as the MNRE) have limited their ability to push for thermal capacity substitution by RE rather than layering new RE capacities on thermal [265]. Initial evidence suggests that most regime actors, including governmental actors, have strategically used delays and deliberate neglect (termed 'ungovernance') as a way of accommodating clean energy initiatives without compromising their own positions [265,269].

Technology transfer from developed countries, another avenue for catalysing socio-technical change, has been a historically important part of India's transition, but the outcomes of transfer mechanisms have been mixed. In the case of India's wind industry, domestic firms with global footprints drove efforts to catch-up with global technology leaders, while the government limited its focus to market formation [273–275]. The success of the wind industry demonstrates the significant role technology transfer has played in India's transition. This trend continues - India is currently seeking to actively leverage international cooperation, such as under Mission Innovation and its research partnerships with the US, UK and EU, to participate in leading innovation processes for cutting-edge technologies [258].

However, India's own inadequate technology-push policies have created an infertile context for sustained technology transfer, causing it to eventually lag behind competitors such as China in RE manufacturing [251]. In theory, technology transfer has multiple conceptualizations, with one being the transfer of hardware and organizational routines, and another being the build-up of tacit knowledge, know-how, and necessary technological capacities within the recipient firm [275,276]. The latter conceptualization depends on the 'absorptive capacity of the recipient country's innovation systems [277–279]. India's record on this

[8] Such as exempting thin-film based solar cells from the DCR regime.

metric - creating an environment for building lasting domestic innovation capabilities - is poor, as evidenced by several analyses of CDM projects [265,277,280–283].[9]

At the sub-national level, more attention is paid to the 'social' side of socio-technical change. This article found a large number of studies related to technology adoption, social preferences, social entrepreneurship and grassroots innovations in India, much of which is focused on small-scale, off-grid, often rural, solar PV experiments [48,284–302]. Rather than focusing on the diffusion of stable technical solutions, these studies reiterate the importance of adapting technologies to local cultural and governance contexts. Narrow top-down framings of solar technologies have limited their diffusion in rural India [292]. Social preferences in India were found to be variable and complex, although normative alignment with green energy is high [303]. Innovative socio-technical models are a pre-requisite for social enterprises to viably provide services to a customer base with a low ability-to-pay [293]. A careful review of this literature, beyond the scope of this article, is needed to extract generalizable and scalable insights.

3.4. Justice perspectives

3.4.1. Energy justice

Extensive empirical evidence from the energy justice literature suggests pervasive and ongoing failures of justice in the rollout of RE infrastructure as well as increasingly exclusionary processes. Recent scholarship has unanimously called for greater scrutiny of green projects, especially large-scale projects [304]. Place-based energy-related confrontations have been documented over diverse contexts: a solar park and a green corridor in Kerala [305,306]; wind energy in the Western Ghats [307]; wind energy in Maharashtra; a solar park in Gujarat [308]; and a solar park in Karnataka [309].

A landmark work on energy justice in India involved a series of case studies on the Charanka solar park in Gujarat, looking at procedural [310], distributional [311] and spatial [312] justice. This work revealed the enclosure of common land most affecting pastoral communities, the use of extra-judicial methods for attaining stakeholder consent, and significant asset dispossession impacting small farmers. The benefits from the park largely accrued to the national and regional levels, to state-level discoms, and to local elites (similar distributive patterns are seen in other cases [306,313]). Others have identified similar patterns of unscrupulous land acquisition, dubbed 'green grabbing' [314,315]. However, some scholars have attempted to put these findings in historical perspective; a systematic review of energy-related conflicts across the globe found renewable energy projects were the least conflictive and entailed lower levels of repression than fossil and hydro infrastructures [316].

Energy justice has also been used as a conceptual tool for thinking through the tensions between short term developmental imperatives (access, affordability) and longer term decarbonisation goals [317,318]. It has also been used as a normative evaluative tool to determine the justness of the current RE policies and solar infrastructure paradigm [174,319–322].

Specifically, scholars have called out scalar biases in India's RE rollout [323–325]. By prioritizing[10] utility-scale infrastructure, India may be foregoing an opportunity for an emancipatory kind of politics, centred on distributed ownership and community participation [174,306,320,325]. While large solar parks have typically been rationalized using the climate crisis and economic development, they largely serve the purpose of neoliberal accumulation while adversely impacting the most vulnerable – especially women and lower caste peoples [306,313,315,326–328]. Adverse impacts of large-scale RE on local ecology, water, livelihoods, food security and waste have also been documented [307,309,329–331]. At the same time, empirical assessments show that existing decentralized RE has also failed to live up to its emancipatory potential; off-grid solar has contributed to some energy poverty alleviation (particularly in improving illumination) but has not yet impacted energy inequality [332]. India's RE transition is thus falling short of its transformative potential regardless of scale.

3.4.2. Just transition

A parallel literature but related literature, employing the term 'just transitions', reveals employment dependencies on coal significantly beyond formal mining jobs. The understanding of 'just transition' in the Indian context is still evolving, with most literature focusing on developing an appropriate framing [204,333–338]. Scholars have broadened the scope of a just transition well beyond replacing lost coal employment, and have argued for the inclusion of identity-issues in coal communities [205,209,339], worker pensions [204], economic diversification for coal regions [338], environmental remediation [340,341] and lost public revenues [212] within its conceptual ambit.

Notably, there are serious concerns about the feasibility of replacing coal jobs with clean jobs in the Indian context. The number of livelihoods dependent on coal is challenging to estimate, although a recent study estimated that nearly 3.6 million people are directly or indirectly employed in the coal mining (~80 %) and power (~20 %) sectors across 159 districts in India [204]. Another estimate suggests that more than 13 million people are employed in coal-linked sectors, such as mining, transport, power, sponge iron, steel, and bricks sectors [341]. Of these, several are contractual or off-roll, making them harder to target under compensatory schemes. While coal-bearing districts in India have substantial solar resources, replacing existing coal jobs with renewable energy jobs would require a substantial scale-up of solar capacity in these regions, adding to system costs [203,342]. The political feasibility of attracting such large capacities to these regions rather than better endowed and economically prosperous regions of the country is low [343].

A silver lining for this issue is that the electricity transition is unlikely to cause a loss of jobs in coal mining and transportation in the near-to-mid-term, i.e. by 2030 [140]. Thus, green jobs in the near term will largely satisfy new job seekers rather than compensate for lost jobs. Mainstream estimates suggests that India could generate nearly 1.3mn [123] and 3.4mn [344] (short and long term) jobs by meeting its 2022 and 2030 RE targets respectively.

4. Discussion

This section attempts to synthesize high-level insights about India's electricity transition, building upon the findings in Section 3. It begins by reflecting on the use of the four perspectives to organize the findings. Subsequently, the discussion is structured along three major cross-cutting questions that transitions scholars may be most interested in.

The search returned a large amount of literature corresponding to the techno-economic and political perspectives, while fewer articles have used the socio-technical perspective in the Indian context. This represents a gap in the literature– the socio-technical perspective is commonly used by transition scholars in developed nations in particular. Further, as suggested by Haldar, Peddibhotla and Bazaz [39], there are several intersections between energy justice and energy transitions. For instance, in this review, the justice perspective intersects with the political and socio-technical perspectives multiple times. For instance, the energy justice literature intersects with political perspective when it discusses the use of extra-legal means of land acquisition and with the socio-technical perspective when it argues against the social impact of energy infrastructures at larger scales.

[9] These analysis suggest that the flawed design of the CDM mechanism may also be to blame.

[10] Scalar bias for utility-scale RE is not just a function of its political and economic attractiveness; it is also driven by the challenges of scaling up distributed forms of RE such as rooftop solar [172,174].

4.1. How fast is India's electricity system transitioning away from coal?

India has made major strides towards RE, but has not yet moved away from coal in any meaningful way. Studies that explicitly address the paradox of India's simultaneous push for coal and RE largely fall on the side of concluding that a paradigm shift towards RE is indeed underway [2,41,42,345,346]. However, two studies [207,217] reached the opposite conclusion, arguing that India is actually transitioning towards greater coal use by pointing towards increasing private investment in the coastal coal value chain. India's thermal fleet is young and coal's multi-faceted political economy lock-ins go well beyond jobs. In addition to these factors, the government's efforts to modernize the coal sector, their attempts to 'clean' thermal power, and their energy mix predictions suggest that a political consensus for moving past coal has not yet been reached.

Regardless of the conflicting diagnoses, most studies concur on one key insight- the complete phase out of coal will be a multi-decadal process [44]. Coal capacity is likely to peak and plateau by the end of this decade rather than be unwound. Neither the national nor any state government has presented a just transition roadmap thus far. India's electricity transition is thus likely to yield avoided rather than reduced emissions this decade.

4.2. How can India's transition approach be characterised?

First, India's electricity transition approach could be characterised as one of episodic opportunism rather than strategic policymaking. Such characterization is applicable to India's approach to climate change more broadly, whereby Indian policymakers have opportunistically, and sometimes in an ad hoc fashion, pursued mitigation actions wherever such actions had significant development co-benefits [347]. However, such an approach has created various internal contradictions, particularly in relation to coal [348]. For instance, policymakers have instituted a clean energy cess of INR 400/ton on coal production which functions as a de facto carbon tax [349–351], but the revenues generated have since been repurposed towards federal taxation compensation [351]. Similarly, India's all-of-the-above capacity addition paradigm, which claims that there are no trade-offs between adding fossil and renewable capacity given India's rapidly growing demand, may need to be abandoned if RE costs keep falling. Indeed, a paradigm shift moment may be on the horizon, with several in-the-pipeline thermal projects looking increasingly unlikely to reach commissioning.

Second, India's electricity transition is acquiring an increasingly top-down nature [352], characterised by a pro-active national government setting energy capacity targets and well-resourced industry incumbents investing in manufacturing and renewable infrastructure. This stands in contrast to the innovation-led bottom up transitions seen more commonly in the sustainability transitions literature. The author's own writing from 2018 [10] had speculated that the renewable sector, owing to its modularity, could enable the entry of a large number of small-to-mid sized private generators into India's power sector which has historically favoured 'gigantism' i.e. modernist, centralized generation. Recent trends have not borne this out; rather than disruption and deeper marketization, the power sector has seen a wave of consolidation as well as the entry of dominant incumbents, paving the way for a more centralized rather than distributed generation model. In FY21/22, acquisitions accounted for 42 % of the total investment in India's power sector [353]. While acquisitions do not necessarily precede monopolization, India's RE sector is decidedly moving away from its decentralized roots [320].

Third, India's electricity transition is witnessing an institutional and political economy shift towards of a 'national champion' model [354]. Established incumbents (such as state-owned enterprises such as Coal India and NTPC, large private GENCOs) have used their expertise, resources, and entanglement with the state to enter India's renewable energy ecosystem and displace or absorb smaller firms [269]. NTPC, India's largest publicly owned thermal power corporation, has announced its intention to install 60GW RE by 2032 [355]. Large, privately-owned fossil incumbents have recently announced large transition bets: the Adani group, a major coal player, plans to invest $70 billion in clean energy, while the Reliance group, an oil refining major, has announced similar plans.[11] These entities have the political connections and financial resources to survive the current policy context (high competition, minimal rents, and capital-intensive growth), and are well-placed to capture significant market shares in renewable energy.

4.3. What role has the state played in India's electricity transition?

The Indian state has exercised a 'modulating' influence on transition [269], actively promoting renewable energy while minimizing disruptions to the existing regimes by delaying enforcement of disruptive policies such as court-mandated pollution norms [356,357], and allowing them to reposition themselves.

It has spearheaded the rise of RE while shifting the onus of energy infrastructure ownership to the private sector. It translates global norms into domestic objectives, coaxes sub-national actors to accelerate the transition, and opportunistically empowers selected niches [163,179,230,358,359]. Evidence from Gujarat, one of the leaders of India's electricity transition, suggests that state intervention in the sector goes far beyond simply inducing private investment [360]. In the solar sector, it played a strategic role, midwifing the sector to maturity [360].

In the absence of bottom up innovation pressures on regime actors, the Indian state is trying to orchestrate the dynamics between regime and niche actors to ensure the regime does not get disrupted. Despite the pro-market reforms of the last two decades, the state is deeply entrenched in the regime. It exercises indirect control over the sector through the banks that provide most infrastructure finance [187,361,362]. In the case of coal, it exercises even more direct control as the historical owner-operator of thermal power generation corporations [163,358] and the owner-regulator of coal resources [10]. It has also prioritized low power tariffs over other objectives (see Section 3.2.3), thus keeping a lid on disruptions to the sector even at the cost of a speedy transition.

This analysis suggests that the Indian state has been equally invested in driving the transition and protecting the sector from disruptions. It remains to be seen what it does if the RE transition gets driven by market forces. Would the Indian state see itself as the protector of the regime, whereby it may attempt to slow the transition, or would it see itself as the custodian of green growth, whereby its role would be to attempt to reform the regime from the inside? Such research questions are explored in the next section.

5. Research gaps

This section highlights six cross-cutting research gaps – theoretical and empirical – in India's transitions literature drawing on the discussion above. Where possible, relevant scholarly literatures and theoretical frameworks are suggested to aid those seeking to fill the proposed gaps.

5.1. Role of the state

The role of the Indian state is now in flux, as it seeks to prioritize energy security through domestic manufacturing. This aspiration is leading to a shift in its role from active market shaper to proactive

[11] https://www.news18.com/news/business/adani-group-plans-to-invest-70-billion-to-turn-india-to-clean-energy-exporter-know-details-5,626,477.html; https://www.reuters.com/world/india/indias-reliance-invest-about-80-bln-green-energy-projects-gujarat-2022-01-13/

industry creator. The state's ambitions to bootstrap and turbocharge industries, such as green hydrogen, may well end up in its own transformation in the upcoming decade. Thus, understanding the changing state-industry relations in the green manufacturing sectors, the state's role in shaping innovation, and the reciprocal influence on the internal logics of the Indian state as a result of its new role in this transition are urgent research questions for transition scholars.

Given the dominance of the state in modulating India's transition, the explanatory power of innovation-centric theoretical frameworks regarding India's transition dynamics needs to be considered carefully [363]. Scholars have argued for the state to be the central unit of analysis for sustainability transition, such as Johnstone and Newell's conceptual work on the state in sustainability transitions [364] and Trencher's work on top-down transitions [352]. Theoretical work around the role of the Indian state would entail multi-disciplinary engagement with existing theories of the state, state-owned entities, state-market relations, state capacities, level of fragmentation and coordination within the state, state finances, state power, and more [361,364].

This approach suits India's state-led transition [163] well. It would enable scholars to mainstream transition issues by directly relating them to poverty alleviation and job creation [365]. Here, scholars could use insights from other Global South and emerging contexts, building upon literatures of developmental states [194,366–370], state capitalism [197,213,361,371,372] and alternative development pathways for industrializing countries [373–375].

5.2. Incumbents and non-state actors

The politics of incumbents– whether and how they are resisting or capitalizing on the transition, and their transition pathways – is an important empirical gap. A meta-analysis of sustainability transitions research has reiterated the importance of focusing on regimes and incumbents as much as niche innovations [376]. Analysing the forward looking business strategies and investment pipelines of key incumbents could be a fruitful research direction for policy scholars seeking to understand the direction in which private capital is leading India's electricity transition. This can be then be contrasted with the stated policies of the Indian state to latent contradictions and conflicts in India's transition governance.

The role of non-state actors such as social movements, civil society organizations, business and commerce associations, and management consultancies in shaping the transition policy has not yet been thoroughly examined in the Indian context (see [377]). The collaborative relations between key bureaucrats and the Solar Association of Gujarat was a key success factor in Gujarat's early progress on electricity transition in the solar sector, whereas inadequate impetus from Bengal's Chamber of Commerce was one of the reasons why RE's initial momentum in the state fizzled [200]. Understanding which actors have shaped the design of consequential policy instruments such as the massive production-linked incentive subsidies for solar PV and battery manufacturing, and through what coordination mechanisms, can shed light on the distributive biases within the emergent policy framework.

Similarly, the role of litigation in shaping the electricity transition can be further scrutinized. For instance, the functioning of entities such as India's Appellate Tribunal for Electricity, an important judicial actor in the regulation of its power sector given its authority to interpret notified regulations [162,192], could be studied to understand how the legislative branch is shaping India's electricity transition.

In summary, this review identifies actor-level analyses as gaps in the understanding of India's electricity transition governance. Hansen et al. [363] concur that the nature of regimes may be different in developing countries and call for more nuanced understandings of institutional change in developing country transitions. Such understanding can subsequently sharpen and inform mid-range or meso-level theories, especially those stemming from socio-technical perspectives.

5.3. Green industrial policy

Sustainability transitions have brought with themselves a new set of geopolitical frictions, as evidenced by the United States raising objections to India's solar promotion policies at the World Trade Organization [378]. Conflicts between developed nations over green industrial and trade supremacy [249,379] could pose serious challenges to late-industrializing countries like India who could be cut off from access to developed country markets for their own green products.

The literature on green industrial policies combines insights from multiple literatures such as green growth, developmental state, rent management and environmental economics. Existing scholarship on green industrial policies suggests that their record in emerging economies is mixed and that success requires a combination of technical and administrative capacities, clear vision-setting, a mix of instruments, adept rent management, exposure to global competition, adaptive policymaking, and policy coordination across multiple objectives [366,379–384]. Given these challenges, transition scholars could analyse various aspects of India's green industrial policy framework, including the policy process behind their formulation, their ex-post effectiveness, and the intersection of these policies with the political economy of the broader power sector. Further, scholars of state capitalism could approach this from the lens of understanding changing state-business relations in India. Existing studies of India's use of green industrial policies in the solar PV and wind sectors such as [194] may offer a useful starting point for this task.

5.4. Core political constituencies and institutional systems

Core political constituencies and institutional systems are clearly under-examined, which underlines the need for disciplinary political science research on India's transition. This review found no accounts of voter preferences and political party ideologies in relation to the transition. The relation between the electricity transition and India's party system or its bureaucratic patterns has not yet been theorized (see for e.g. [385]). Micro-politics of power sector bureaucracies especially need to be understood better to understand a potentially powerful force shaping the implementation of India's transition policies.

Some politically significant groups such as labour unions have begun articulating their visions for a fair transition [335]. Three factors influence their views on the transition – heightened exposure and vulnerability to climate change, a history of public ownership of energy assets, and a history of union-led resistance against top-down reforms. Representatives of labour unions have argued for a participatory, public sector-led industrial policy, decentralized energy collectives, rehabilitation of coal areas and redeployment of the coal sector workforce [336].

5.5. Economic diversification and social protection in just transitions

Redeploying coal workers to solar industries is a huge challenge in Indian states, as highlighted in Section 3.4. Scholars have additionally argued for economic diversification in coal bearing regions to absorb the large direct and indirect coal labour force. This is challenging due to huge variability in employment patterns and coal prospects across districts [341]. District-levels case studies analysing economic diversification plans for India's coal regions and identifying alternate industries for diversification are currently missing. One such study, in the Ramgarh district of Jharkhand [338] confirmed high dependency on coal for incomes, neglected social and physical infrastructure and poor governance in non-coal sectors. Another study in Angul, Odisha has unpacked public finance contributions from coal at district and state level [215].

The literature on India's just transitions has rightly revolved around employment considerations, however it needs to be complemented by an equally robust discourse on social protections for India's vast populations in coal regions. Extending such protections would be important in those districts where alternate job creation efforts do not succeed. Transition scholars could collaborate on these questions with social policy researchers and practitioners who have deep understandings of existing social protection schemes such as the Mahatma Gandhi National Rural Employment Guarantee Scheme.

5.6. India's development pathway

Unlike developed country contexts, electricity transitions in developing countries depend significantly on future electricity demand patterns which in turn are a function of macro-structural choices, particularly those related to urbanization and industrialization.

An effort at unpacking recent major energy-emissions modelling studies reports that the implied development and energy transition pathways in these studies differ significantly. For instance, IEA's India Energy Outlook study assumes an unprecedented services-led growth pathway for India [386] while a TERI-Shell study assumes an increase in the share of the manufacturing to 25 % of GDP by 2025 in line with government targets [387]. These varying assumptions could significantly alter the studies' message on the optimal energy mix, the aggregate investment needed, the rate of transition and so forth.

Transition scholars, particularly those from the energy and economic modelling community, could focus on deepening our collective understanding of structural decisions that India is locking itself into and develop corresponding datasets.

6. Conclusions

In this review, I aimed to briefly discuss insights on India's electricity transition across a multiplicity of disciplinary perspectives. In addition to presenting a large number of articles in a narrative form, I have also drawn some cross-cutting insights on India's transition, such as the role of the state in modulating the transition in the absence of a strong innovation system and incumbents as key actors driving India's transition.

This article makes three contributions to the global literature.

First, this article contributes an Indian case to the budding literature on national sustainability transitions. The literature on India's electricity transition is growing, necessitating streamlining and field-shaping. Despite numerous existing reviews, the literature remains fragmented, with limited cross-pollination between the academic and policy literatures. This review sought to taxonomically organize this complex literature, making it more tractable for future scholarship.

Second, it highlights a number of research gaps that can serve as a useful set of sign posts for both transitions scholars and geographically-focused India scholars.

Third, this work adds to the understanding of transitions in developing country contexts. Insights on India's transition pathway could be of substantial interest to development-focused audiences in emerging economies. While not exclusively the remit of developing countries, I emphasize the centrality of justice in understanding national energy transitions in developing contexts and highlight it by adding this cross-cutting perspective as an organizing category in addition to three broad perspectives on energy transitions identified by Cherp et al. By explicitly calling out justice related variables and themes as central, this paper calls for transition researchers to be reflexive about the fact that meta-theoretical frameworks could uncritically replicate modernist conceptualizations of national transitions as being concerned primarily energy related systems – markets, technologies, policies – and not with vulnerable people.

Based on the findings of this work, I propose a few forward-looking priorities for strengthening the knowledge base on India's transition:

- Building the theoretical underpinnings of the politics of India's electricity transition – the role of the state, the party and voter preferences, how actors shape the policy process – is an urgent task.
- More meta-synthetic work in priority areas, particularly modelling India's development pathway, could yield rich policy-relevant insights.
- Consolidating the vast literature on microgrid experiments in order to extract generalizable insights about grassroots innovation in India.
- More attention from the policy community to the socio-technical transitions literature, given the growing importance of manufacturing and innovation in India's transition.

This paper does not claim to be a faithful or comprehensive review of India's electricity transition. Rather it aims to be a faithful reflection of the literature on India's transition. In this sense, the narrative and analysis here is likely to carry forward researcher biases or misapplications of theoretical frameworks designed for contexts that are different from that of India. There are several nuances on India's transition which are not yet captured by either academic or grey literature. Further scholars have advised against deriving "cross-cutting" insights across epistemologically distinct literatures and analytical approaches [17,18]. They have also proposed sound ways of 'bridging' and 'aligning' across approaches rather than integrating insights from distinct theoretical perspectives. I acknowledge that this review does not have as sophisticated a method, which is why this work is only a modest first step towards understanding India's electricity transition.

A truly comprehensive, co-produced research agenda accounting for plural forms of knowledge [20,388,389] is needed to guide this research community in their pursuit of producing more theoretical and policy-relevant insights on India's electricity transition.

Abbrevations

IAM	Integrated Assessment Models
STS	Science and Technology Studies
Discom	Electricity Distribution Companies
RE	Renewable Energy
NAPCC	National Action Plan on Climate Change
PV	Photovoltaic
RPO	Renewable Purchase Obligations
NIS	National Innovations System
NDC	Nationally Determined Contributions
GWh	Giga Watts/hours
CCS	Carbon Capture and Storage
MT	Million Tonnes
NGO	Non-Government Organisation
GBI	Generation Based Incentives
AD	Accelerated Depreciation
NSM	National Solar Mission
RECs	Renewable Energy Certificates
DCR	Domestic Content Requirements
PLI	Production-Linked Incentive
RD&D	Research, Development and Demonstration
R&D	Research and Development
FDI	Foreign Direct Investment
CDM	Clean Development Mechanism
GENCO	Generation Companies
SOE	State Owned Entity
EV	Electrical Vehicles
SECI	Solar Energy Corporation of India

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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