Energy Research & Social Science 71 (2021) 101815

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Solar federalism: What explains the variation in solar capacity additions by India's states?

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ARTICLE INFO

Keywords:
India
Solar
Renewables
Climate change
Mitigation
Energy transition
Federalism

ABSTRACT

In 2014, India embarked on an ambitious effort to scale-up solar electricity. Despite a major top-level push by the central government, India's states show stark variation in their performance as measured by installed utility-scale solar capacity. This paper seeks to explain that puzzle. We first code 19 of India's states on utility-scale solar performance and classify them into categories of *Achievers, Middlers, Laggards,* and *Marginals*. We then identify plausible and testable factors of performance including solar irradiance, power deficits, distribution company financial health, coal costs, land access, and political alignment of the state with the central government. Overall, irradiance, distribution company health, coal costs, and land access were the most influential, but counter-intuitively, political alignment was minimally relevant. Achievers tended to have some favorable combination of irradiance, power deficits, distribution company health, coal costs, and in some cases land access. Marginals were associated with unfavorable Discom health, land access, and coal costs. Patterns for Middlers and Laggards were less clear. To identify additional state-specific factors that affected performance, we also carry out detailed case studies for three states - Karnataka (Achiever), Madhya Pradesh (Middler), and Maharashtra (Laggard). These show the importance of political and bureaucratic leadership, path-dependence, and interest group influence. Our findings highlight the challenges of energy transition pathways that may be relevant to other countries with similar federal systems.

In 2014, India, under its then new Prime Minister Narendra Modi, adopted an ambitious target to increase the amount of installed solar electricity capacity to 100 GW by 2022. Motivated by his own experience in Gujarat and seeing an opportunity to project an image of modernity at home and deepen partnerships abroad, Modi embraced a major expansion of solar electricity in the lead up to the Paris climate negotiations [1]. Even though it had a preexisting National Solar Mission, India at the time only had about 2.5 GW of solar installed. Since then, India has installed more than 30 GW of solar, most of it large utility-scale solar plants. Still, solar still only provides a small share of the country 's electricity, less than 4% in 2019 [2].

India has 28 states and 7 centrally-administered "union territories." In addition, the national capital of Delhi has partial statehood. The country has twice the population of the European Union with 22 major languages. Coordinating and implementing policy in a large diverse, democratic polity such as India is always a challenge, though state-level autonomy also provides opportunities for local policy innovation and experimentation. Both aspects are evident in the electricity sector, which is in the "concurrent" list of the Indian constitution with powers shared between the center and states.

India's experience with solar and renewables more broadly is of great consequence for the world. India is the fourth largest source of greenhouse gases, responsible for about 7% of fossil fuel derived CO_2 emissions in 2018,[1] with emissions rising rapidly as the country becomes richer [3]. Electricity is now and prospectively the largest source of India's greenhouse gas emissions. If India is to displace coal as a significant source of electricity and avoid millions of tons in greenhouse gas emissions and improve air quality, it will have to successfully tap more of its solar potential [4]. This will require the country to navigate its federal structure and address the problems in underperforming states.

In spite of a major top-down solar push since 2014 by Modi (widely seen as a centralizer), India's states show stark variation in their performance as measured by solar capacity added, which is not wholly attributable to physical resource potential. This paper seeks to explain this puzzle. This article is part of an emergent literature on the geography and spatial variation in clean energy transitions [5,6]. It is the first piece to our knowledge that systematically seeks to explain the variation in solar capacity installation between Indian states, though Dubash,

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[1] India's contribution to global carbon pollution is much lower than these numbers would suggest from per capita and historical emissions standpoints.

https://doi.org/10.1016/j.erss.2020.101815
Received 10 June 2020; Received in revised form 17 August 2020; Accepted 1 October 2020
Available online 25 December 2020

State	Population (Million)	Installed Capacity (MW)	Pipeline Capacity (MW)	Net Capacity (MW)	Peak Demand (MW)	2022 Target (MW)
Andhra Pradesh	49	3488	1325	4813	9459	4917
Assam	31	41	0	41	1865	2762
Bihar	103	125	0	125	5115	2493
Chhattisgarh	26	185	0	185	4444	1783
Gujarat	60	2046	2065	4111	17053	8020
Haryana	25	41	0	41	10270	4142
Jharkhand	33	16	0	16	1339	1995
Karnataka	61	6500	1233	7733	12877	5697
Kerala	33	78	22	100	4245	663
Madhya Pradesh	73	1927	202	2129	13815	5675
Maharashtra	112	1474	2075	3549	23864	11926
Odisha	42	334	101	435	5357	4772
Punjab	28	837	0	837	12638	2377
Rajasthan	69	3922	4070	7992	13276	5762
Tamil Nadu	72	3360	561	3921	15483	8884
Telangana	35	3521	152	3673	10815	4917
Uttar Pradesh	200	840	1155	1995	20498	10697
Uttarakhand	10	224	0	224	2216	900
West Bengal	91	89	0	89	9130	5336

Fig. 1. Key utility-scale solar statistics for states under consideration. Sources – CEA, 2020, Bridge to India, 2019, Census of India, 2011.

Kale, and Bharvirkar provided a foundational survey of state-level dynamics in Indian electricity [24] and Sareen and Kale compared two specific states [7]. Much India-specific solar research focuses on off-grid solar, which comprises a relatively small share of India's installed solar capacity, though serves important communities [8–10]. Since more than 85% of the scale-up to date has been utility-scale solar plants, this paper focuses on that segment [11].

We limit our study to 19 states with a population of more than 10 million, which together represent about 97% of the country's population.[2] These are classified according to installed solar capacity in 2019 into four categories named Achievers, Middlers, Laggards, and Marginals, ranked in descending order of performance. We then consider seven candidate factors that could explain state-level performance, namely physical irradiance, power deficits, distribution company (Discom) health, coal costs, land access, grid congestion (intra-state), and political alignment (with the central government.) Analyzing the data for each factor, we code whether it was favorable or unfavorable in terms of stimulating utility-scale solar capacity additions.

Our results allow us to conclude which of these seven factors is associated the most with solar success. Further analysis reveals some common configurations or pathways to Achiever, Middler, Laggard, and Marginal status. In a large complex country like India, state-specific factors could also play an important role. To understand local variations better and to reveal more granular detail in state solar pathways, we pick three states for deeper analysis namely Karnataka (in the Achiever category), Madhya Pradesh (Middler), and Maharashtra (Laggard).

Our fieldwork included 25 elite interviews conducted between late 2018 and early 2020 and included in-person elite interviews in Bangalore, Delhi, Bhopal, and Mumbai as well as additional follow-up phone calls and emails. The interviewees included senior bureaucrats, private sector representatives, sector consultants, specialized media, and market analysts.

We conclude that solar irradiance, Discom financial health, coal costs, and land access are the factors most associated with solar performance by states. Power deficits emerged as key in one of our case studies. To our surprise, political alignment was only minimally associated with good solar performance. Intra-state grid congestion, to the extent we were able to ascertain it, was associated in a reverse manner – well-performing states also had higher grid congestion, which may possibly indicate reverse causality.

We also identified pathways to the best and worst performers. The highest solar performers (Achievers) tended to have excellent irradiance, healthy Discoms, expensive coal, power deficits, and some land. The worst performers (Marginals) were clearly associated with poor Discom health, land challenges, and low coal costs. States that fell in-between showed no clear patterns with the factors as a group. Case studies demonstrated the additional importance of state-specific factors such as path-dependence, interest groups, and leadership across all categories examined.

The article is organized as follows. The first section groups the states according to their solar performance. The second situates the electricity sector generally, and the solar sector specifically, within India's complex federal developmental dynamic. The third section outlines our methods and working hypotheses for explaining the variation in state solar performance. Section four tests these explanations at a multi-state

[2] The former state of Jammu and Kashmir was bifurcated and downgraded to two union territories in 2019 and is therefore excluded from this study. Given disputes with Pakistan and China and major difficulties of power evacuation, this territory in any case faces major challenges in exploiting its solar potential. The territory of Delhi has partial statehood and is highly urbanized, with little scope for utility-scale solar. It is therefore also excluded.

Classification	State	Installed Capacity (% of Peak Demand)	Net Capacity (% of Peak Demand)	Installed Capacity (% of Target)
Achievers	Karnataka	**50.5**	60.1	44
	Andhra Pradesh	**36.9**	50.9	52
	Telangana	**32.6**	34.0	45
	Rajasthan	**29.5**	60.2	43
Middlers	Tamil Nadu	**21.7**	25.3	57
	Madhya Pradesh	**13.9**	15.4	41
	Gujarat	**12.0**	24.1	47
Laggards	Uttarakhand	**10.1**	10.1	41
	Punjab	**6.6**	6.6	38
	Odisha	**6.2**	8.1	44
	Maharashtra	**6.2**	14.9	50
	Chhattisgarh	**4.2**	4.2	40
	Uttar Pradesh	**4.1**	9.7	52
Marginals	Bihar	**2.4**	2.4	49
	Assam	**2.2**	2.2	36
	Kerala	**1.8**	2.4	44
	Jharkhand	**1.2**	1.2	149
	West Bengal	**1.0**	1.0	58
	Haryana	**0.4**	0.4	40

Fig. 2. Classification of states by utility-scale solar performance.

aggregated level, by coding factors for each state. It then identifies pathways to performance based on the coding. The fifth provides a deeper case study analysis for three Indian states, each from a different performance category, highlighting local factors that influence performance. The final section concludes and points to possibilities for future research.

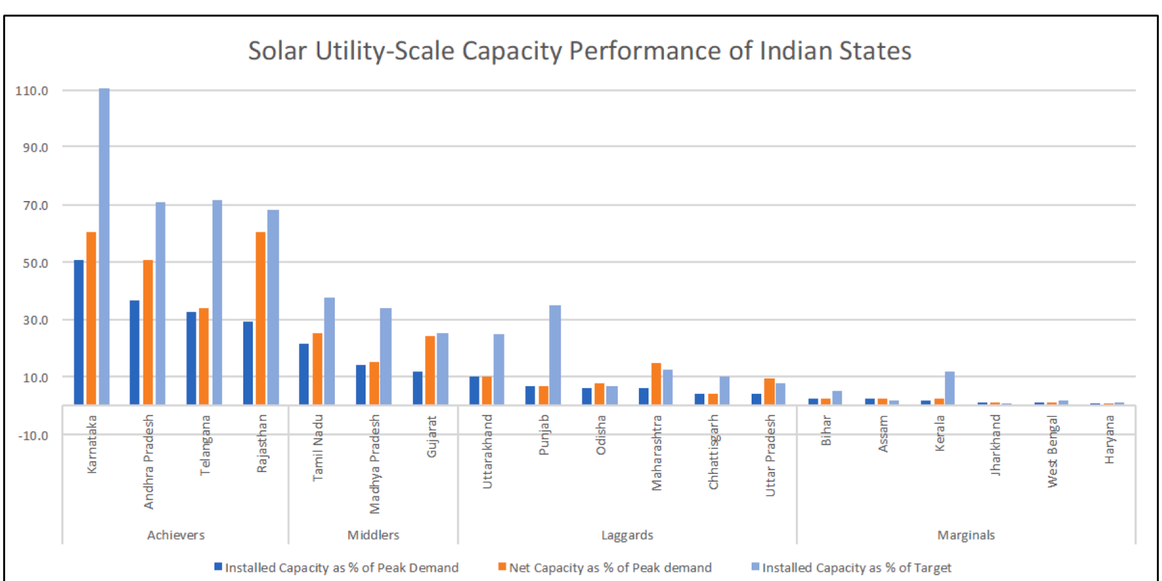

Fig. 3. Graphical representation of normalized capacities and state rankings.

1. Solar performance of Indian states

India's states demonstrate large variations in utility-scale solar scale-up. Key utility-scale solar statistics for the 19 states (ranked in alphabetical order) in our study are presented in Fig. 1. Installed capacity is the actual utility-scale solar capacity online as of September 30, 2019. Pipeline capacity is the capacity in progress expected to come up within the next year or two. Net capacity is obtained by summing the two values.

The first step in our analysis is to rank states in terms of their solar performance. The raw data in Fig. 1 cannot be used for this purpose, as states are vastly different in terms of their population, economic conditions, and therefore power consumption. Peak electricity demand for the state, also shown in Fig. 1, can serve as a denominator for normalizing the capacity data. India's central government has set solar capacity targets for each state for 2022, and therefore this value can also be used as a basis for normalization.

We consider the normalized installed capacity as the most useful metric however, as including future capacity projections (i.e. net capacity) comes with a degree of uncertainty given current market volatilities, especially with the COVID-19 outbreak. Normalization by state-level targets yields us practically the same result, as state level targets have been set according to power demand in that state.

Normalization allows us to classify the states being considered into four groups according to their level of utility-scale solar performance. Figs. 2 and 3 show this classification in tabular and chart form. The top four states - Karnataka, Andhra Pradesh, Telangana, and Rajasthan - clearly stood out as having the highest levels of normalized installed capacity and were categorized as *Achievers*. The other three groups were determined as follows. *Middlers* (Tamil Nadu, Madhya Pradesh and Gujarat) have substantial levels of installed capacity, though less than that of Achievers. They are also continuing to add capacity – in the case of Gujarat, the pipeline capacity values are high.

Laggards have installed capacities at levels below Middlers. In addition, they had either appreciable capacity installed early but then stalled completely (e.g. Punjab), or else were late movers and are adding significant capacity only now (e.g. Maharashtra). Uttarakhand, Punjab, Odisha, Maharashtra, and Uttar Pradesh fell into this category. Finally, the worst performers, called *Marginals*, have both minimal utility-scale solar capacity currently and in the pipeline. This includes Bihar, Assam, Kerala, Jharkhand, West Bengal, and Haryana.

2. Indian federalism and the electricity sector

India has been a unified nation-state since decolonization in 1947, but shows huge diversity among its states, largely drawn on the basis of language. Varshney argues that language became central to the federal structure in part due to geographic concentration on that basis in a way that religion could not after Partition [[12], p. 45]. Stepan described it as a "holding together" federalism, different from the United States' "come together" variant [13].

As Tillin notes in her book on Indian federalism, federal structures share governance and distribute responsibilities: "In federal systems, at least two levels of government—in India's case, the Center and the states—share in the task of governing but have their own spheres of autonomy" [[14], p. location 91]. India's model of federalism, what she describes as centralized but flexible, is a byproduct of Partition and reflects the era when government centralization was a feature of many countries pursuing development in the wake of independence. However, India was centralized with a "strong degree of interdependence between the center and states." At the same time, India's constitution is "permissive" with respect to amendments, which could facilitate "flexibility to tackle issues, especially those concerning the accommodation of diversity…." [[14], p. location 126], [[15], p. 200].

In the Nehru era post-independence, the country centralized state development with a strong bureaucracy and government control of many sectors of the economy, including generation of electricity. Electoral dominance at the national level (though not necessarily in the states) by the Congress Party facilitated this centralization. In the 1980s, the country embarked on paths of economic liberalization that increased economic growth rates but also widened disparities between states.

Explaining this divergence between the developmental successes of states in a federal system has been attempted by several scholars [16–19]. Jenkins argues that federalism has given reformers at the center some space to act even as the distribution of powers has been able to manage internal conflicts. His work also highlights the importance of informal institutions in Indian policy outcomes. Sinha's work highlights both continuity and change in Indian federalism and the country's economic pathway. She notes that during the more centralized period Indian states competed with each other "vertically…for centrally-determined resources," the liberalization period saw states competing "horizontally,“ i.e. more directly with each other and "for resources from a wider variety of actors." Sinha attributes the increased divergence between states in the reform era to four factors – political alignment with the center, subnational institutions' impacts on transaction costs, social bases, and inter-state competition [18,19].

Power sector reform was an important part of this liberalization agenda in a country with state-owned institutions dominating the electricity sector, but with hundreds of millions in rural areas without reliable access. Post-liberalization, the sector was "unbundled" or split up with different entities handling generation, transmission, and distribution. Along with unbundling, privatization was also pushed. However, while generation was substantially privatized, transmission and distribution remained predominantly state-owned [20–23].

A recent seminal volume edited by Dubash, Kale, and Bharvirkar analyzed the political economy of power sector reform in India at the state level [24]. It argued that, even if policy originated in New Delhi, implementation of that reform agenda "has taken place in the country's scattered provincial capitals, by state-level bureaucrats, politicians, and engineers" [[24], p. 2]. The volume, building upon an earlier historical work by Kale [25] emphasized path-dependence and dynamics of interest groups.

The advent of the Modi government has controversially been marked with growing efforts to recentralize a number of policies, including those in the electricity sector. Centralization however may have its limits, as the center always depends on state governments for implementation, even as states depend on the center for finance [[14], p. 748], [7].

The Indian central government has backed solar scale-up with a variety of policies, such as limited subsidies, competitive bidding framework, payment guarantees through the newly founded demand aggregator Solar Energy Corporation of India (SECI), central generators taking on solar targets, and a rescue plan for Discoms with the acronym UDAY.

Discoms in many large states face significant under-recovery of costs and are saddled with huge debts, partly due to subsidized power supplied to farmers and high technical and commercial losses. Tariff increases are politically challenging due to large voting power of farmers. This acts as a major constraint on the expansion of solar power, as Discoms are reluctant to buy more electricity from renewables in the face of existing long-term payment lock-ins with coal plants.

UDAY was launched with much fanfare in 2015 but is now widely seen as a failure. Though stricken Discoms temporarily regained much of their health, they have not implemented other reforms like reducing grid losses and tariff revisions to improve their long-run profitability.

Like Kale and Dubash et al., we see the need to anchor an understanding of state variation in solar scale-up in the political economy of the country and individual states [24,25]. We seek to build on their approach by delving deeper and more specifically into the question of utility-scale solar growth and attempting to apply a common analytic framework to India's disparate states. Our factor-based explanation for utility-scale solar success brings the varied experiences of states under a unified rubric, while equally emphasizing state-specific dynamics.

3. Methods and hypotheses

What might explain the variation in Indian state performance in solar scale-up? To answer this question, we turn to qualitative case study methods. Given the relatively small number of states and the large number of possible factors, a conventional regression-type analysis is not feasible. As discussed in Section 2, we coded the relative performance of different Indian states on solar capacity additions and then grouped them in to four categories of performers. In this section, we identify plausible factors that could explain the variation. Given the interdisciplinary subject matter, we draw on a variety of indicators, including physical/material indicators (of solar irradiation, land availability), financial indicators (distribution company health, coal costs), and political factors (alignment with the central government) [26]. These indicators repeatedly came up during our interviews and have also been cited individually as barriers or factors in other articles on Indian solar. For each indicator, we sought a suitable proxy indicator from different sources to code each dimension. We evaluate each factor to assess whether it generally supports our hypothesis.

Recognizing that states that led or lagged in capacity additions may share several characteristics, we rely on what George and Bennett call "configurations" or "conjunctions" of factors to assess whether different kinds of states shared certain attributes. Here, we look for patterns and shared pathways to high and low performance [[27], p. 235]. This approach is based on what scholars call the "family resemblance" approach in set theory [28]. These states may not share all the same characteristics but a number of them may be central to the performance of leading and lagging states. We treat states as belonging to the same set if they shared similar performance levels and some common characteristics. Our method has the virtue of identifying pathways to performance among Achiever and Marginal states, but we observe more heterogeneity among Middlers and Laggards. Other approaches like Qualitative Case Analysis (QCA) might offer ways to identify discrete intermediate pathways with more precision [29].

Together, this portrait based on the conjunction of different indicators can only tell us so much about how these factors come together in different state contexts. Local stories are crucial to understand the sharp variance in state performance. We also identify a number of outlier cases that we would have expected based on the factor codings that either over-performed or under-performed in solar capacity additions. These cases such as Madhya Pradesh (a relative over-performer) and Maharashtra (a relative under-performer) serve as inclusion criteria for more detailed process-tracing, allowing us to surface additional factors in those states [27]. This motivates our case studies for three particular states (Karnataka, Madhya Pradesh, and Maharashtra), which reveal the importance of state-level leadership, path-dependence, and interest groups.

To code the cases, we first considered candidate factors that could be applied to all states. Below we lay out our seven working hypotheses, each providing a possible explanatory factor. We subsequently test the association of these factors with solar performance data.

First, zones of higher physical solar radiation are the most profitable for developers and the most attractive sites for solar parks. *Thus, all else equal, we expect states with higher solar irradiance to perform better.*

Second, more power plants are typically planned and built when there is an expectation of greater power demand. India has until recently been a country with significant power deficits, thus we expect this factor to play a major role. *Our expectation is that states with high power deficits will be more likely to scale-up demand.*

Third, as the last section discussed, India's Discoms have been in parlous economic health. Though some metric of overall state income could be considered an independent factor in its own right, Discom finance may be a more important, proximate measure of a state's likelihood of scaling-up solar, even in wealthy states since the Discoms are the entities that purchase power. *Our expectation is that states with good Discom health will be more likely to scale-up solar electricity.*

Fourth, domestic coal is cheap to mine in India but expensive to transport (typically by rail) over longer distances. The ready availability

Classification	State	Solar Irradiance	Power Deficit	Discom Health	Coal Costs	Land Access	Political Alignment
Achievers	Karnataka	**Very High**	**High**	**Moderate**	**Moderate**	Low	Low
	Andhra Pradesh	**Very High**	**Moderate**	**Moderate**	**High**	Low	**High**
	Telangana	**Very High**	**High**	**Moderate**	Low	**Moderate**	Low
	Rajasthan	**Very High**	Low	Poor	**High**	**Moderate**	**High**
Middlers	Tamil Nadu	**Very High**	**Moderate**	Poor	**High**	Low	Low
	Madhya Pradesh	**High**	Low	Subpar	**Moderate**	**Moderate**	**High**
	Gujarat	**Very High**	Low	**Very Good**	**High**	**Moderate**	**High**
Laggards	Uttarakhand	**High**	**Moderate**	**Good**	**High**	N/A	**High**
	Punjab	**High**	**Moderate**	**Moderate**	**High**	Low	**Moderate**
	Odisha	**High**	**Moderate**	N/A	Low	Low	Low
	Maharashtra	**Very High**	Low	**Moderate**	**Moderate**	Low	**High**
	Chhattisgarh	**High**	**High**	Subpar	Low	Low	**High**
	Uttar Pradesh	**High**	**High**	Poor	**High**	Low	**Moderate**
Marginals	Bihar	**High**	**High**	Subpar	Low	Low	**Moderate**
	Assam	Moderate	**High**	Subpar	N/A	Low	**Moderate**
	Kerala	**High**	**Moderate**	Subpar	**High**	Low	Low
	Jharkhand	**High**	**High**	Very Poor	Low	Low	**High**
	West Bengal	Moderate	Low	**Moderate**	Low	Low	Low
	Haryana	**High**	Low	Subpar	**High**	Low	**High**

Fig. 4. Hypothesized factors for analyzing pathways to performance (normalized using methodology in Appendix A).

and affordability of coal could discourage states to ramp up solar. Most Indian coal mines are located in the east and east-central regions. States close to mine pitheads might find coal plants more attractive to build rather than solar. Distance from coal pitheads, i.e. more expensive coal, may increase a state's enthusiasm for solar. *Our expectation is that states without access to cheap coal are more likely to scale-up solar.*

A fifth limiting factor is land. India is very densely populated throughout much of the country. Project developers often prefer land closer to infrastructure and grid access, which means acquisition of agricultural land is key. However, landowners (typically farmers) in India are highly resistant to giving up their only asset which they see as a form of insurance. *Our expectation is that states with fewer land access challenges will be more able to scale-up solar.*

Sixth, the central government, led by Modi's BJP during the period of our study, has made solar scale-up a particular priority as detailed above. *We expect states run by the BJP or its formal allies to be more supportive of solar scale-up than those led by opposition parties.*

Seventh, some states have poorer intra-state grid quality and may face challenges of evacuating solar electricity from sites of generation, which would act as a barrier for solar scale-up. *Our expectation is that states with lower intra-state grid congestion are more likely to adopt solar scale-up.*

The above factors are by no means the only ones that might drive solar success or failure in a state. State-level leadership is also critical in achieving success (as came out in our interviews and will be clear in the case studies below). Just because a state faces favorable conditions based on the preceding factors, it might not avail itself of solar electricity because the politician in charge is not so inclined. Additionally, in India, the bureaucracy is powerful, autonomous to an extent, and key to implementation success of any political initiative. Thus, bureaucratic leadership is also important. However, these factors are difficult to measure and test in a structured manner. Therefore, we have not included them in our factor coding but rely on interviews and case studies to highlight their mechanics and importance.

4. Factor coding and pathways to performance

Multiple factors, national and local, are responsible for a state's solar performance. For any given state, it is a particular combination of factors that is of most relevance. However, before we look at groups of states for patterns it is useful to see which of our six core hypothesized factors–solar irradiance, power deficits, Discom health, coal costs, land access, and political alignment–seem to do a better job at being associated with better solar performance.

Fig. 1 lays out the final tally for all 19 states considered, with states ordered, as earlier, in decreasing solar performance from top to bottom of the table, with corresponding normalized values for each factor listed. Factors favorable toward better solar performance are coded in bold. The methodology for coding each factor is detailed in Appendix A.

We initially considered grid congestion and coded that factor for all nineteen states. Grid congestion appears to be an anomalous factor with a reverse association visible. As many as five of the top seven states show evidence of grid congestion, whereas the ratio is exactly reversed for Marginals. The apparent reverse association of grid congestion might indicate that any causality present may run backwards – i.e. states doing lots of renewables report more curtailment and grid congestion issues. Excellent examples are Tamil Nadu and Rajasthan where a judicial trail of curtailment and congestion issues is well documented. The data we could find for this factor data was also uneven. To summarize, we lacked the necessary confidence in our data to include that factor in our analysis. Therefore, grid congestion is not included in Fig. 4 below (but is tabulated in Appendix A).

Of the groups defined, Achievers and Middlers are strong performers. Together these seven states account for 83% of the installed utility-scale solar capacity in the country. Including capacity in the pipeline, the top seven states will still account for 81% of the capacity.

The seven Marginals on the other hand are consistently poor performers and together represent just above 2% of the nation's installed utility-scale solar capacity. This will shrink further to barely above 1%, after pipeline projects are implemented. The Laggards represent a mixed/transitional category with suboptimal performance, though Maharashtra and Uttar Pradesh are beginning to scale up more rapidly.

We hypothesize that Achiever and Middler states would tend to share certain favorable features such as good solar irradiance, power deficits, good Discom health, expensive coal, and adequate access to land while Laggard and Marginal states would lack these features. In the analysis that follows, we seek to identify to what extent our hypotheses bear out and what apparent configurations or patterns emerge from the data.

To explore which of our six hypothesized factors best correspond with state performance, it is more useful to focus on the two ends of the performance spectrum - Achiever/Middler set (i.e. the top seven states) and Marginals (the bottom six states).

India is particularly rich in solar irradiation. The country has considerable untapped potential for additional solar, more than 700 GW [30]. As Fig. 4 indicates, almost all states are assessed as High or Very High in this resource. As we might expect, most of the highest endowed states are indeed strong performers. But several other states with excellent irradiance show limited or minimal performance. These include Maharashtra, Kerala, Uttar Pradesh, Jharkhand among others. Thus, physical solar endowment does not naturally translate into large and fast capacity adds.

Considering power supply deficits, four of the top seven states do have moderate to high rankings. Also, our Karnataka case study (see below) shows that a challenging power supply situation was a major motivator for the state's push for solar. On the other hand, Rajasthan, Madhya Pradesh and Gujarat did well despite low power deficits. Note that Rajasthan and Madhya Pradesh particularly have adopted an export-oriented model for solar power, so power deficits would not be expected to impact their motivation to ramp up solar. However, four of the seven Marginal states also show moderate/high power deficits.

The Discom health of three of the top seven states (i.e. Achievers and Middlers) averaged over the period under study is moderate and, in the case of Gujarat, very good. Two states, Rajasthan and Tamil Nadu have low rankings, while Madhya Pradesh is assessed as subpar. Note that Rajasthan's auctions are predominantly led by the central government, thus greatly reducing the relevance of Discom health for scale-up success. Clearer conclusions can be drawn from examining the seven Marginal states. Only one of these has a relatively healthy Discom (West Bengal) while the others have poor rankings.

Turning to coal costs, six of the top seven states have high or moderate coal transport costs. Telangana is the only well-performing state with low coal costs. In the Marginals group, three of the seven states have high coal costs.

Land access scores indicate that the four states with relatively good land access, namely Telangana, Rajasthan, Madhya Pradesh, Gujarat, all are in the Achiever/Middler set. All Laggard and Marginal states have land availability challenges. Finally, no clear pattern is seen in the case of political alignment with both the top seven and bottom seven states showing similar levels of alignment.

Which of our six hypothesized factors are associated with good performance? Stronger association is seen only in cases of irradiance, Discom health, land access, and coal costs. Power deficit shows an association largely with strong performers. Political alignment shows little association across all groups. We now use our data to try and identify possible pathways to high and low solar performance, with conclusions for states outside our case studies as indicative rather than definitive.

4.1. Pathways to achiever status: Healthy Discoms, expensive coal, power deficits, land availability

Achiever states have at least three factors coded as favorable in all cases. Power deficits, Discom health, and coal costs are at moderate to high levels in three of the four Achiever states and good land availability is present in two. Our case study of Karnataka (see below) showed that power deficits and coal costs played a major role in pushing the state to adopt solar. Achiever states therefore had multiple reasons to pursue solar – they needed power, their Discoms were in good health to commit to solar power purchases, coal was less competitive, and land was also (in some cases) in good supply.

Some outliers can however be noted. Rajasthan appears to be an outlier among the Achievers, with poor Discom health and low power deficits during the period under study. The former particularly ought to have made solar scale-up much more challenging. However, Rajasthan's auctions were almost entirely central government led with the goal of exporting generated electricity to other states. This coupled with good land availability could have mitigated these adverse effects.

Two states – Uttarakhand and Gujarat – might have ended up as Achievers based on this data but did not. Uttarakhand is another outlier – with five of six factors favorable to solar scale-up, it could have done better. However, other factors, such as suitability of land (the state is mostly hilly/mountainous) could have been a barrier in this case. A crucial factor such as land, if highly unfavorable, can easily override multiple favorable factors for a state.[3]

Gujarat appears to be another under-performer with five of six factors favorable, yet finishing below all other Achiever and Middler states. State-specific factors such as leadership and path-dependence best explain Gujarat's uneven story. Gujarat was an early adopter of solar but got locked in to higher prices which deterred subsequent deployment [7,31]. However, Gujarat's high pipeline capacity (Fig. 1) indicates that it may recapture its past high rankings.

4.2. Pathways to Middler status: No clear pattern

The limited number of states in the Middler category makes it harder to draw definitive conclusions on a common pattern. Indeed, two of these three states (Gujarat and Tamil Nadu) would have been in the Achiever category had we done this evaluation a couple of years back.

All Middlers have at least three factors as favorable, and all also have moderate-to-high coal transport costs. Gujarat however has four, which makes it a relative under-performer (see above). One of the Middlers, Madhya Pradesh, was also one of our case studies. Strong local leadership overcame subpar Discom health and low power deficits (see below). Tamil Nadu's substantial capacity adds despite poor Discom health can be partly explained by the much higher tariffs it awarded to developers.[4] In this case, strong irradiance, favorable power deficits, and coal costs could have been drivers as well.

Overall, these cases show multiple factors at play for the Middlers. State-specific factors may do most of the work in this category.

4.3. Pathways to laggard status: Land challenges and power deficits

This category consists of six states of which one, Maharashtra, was also the focus of a case study. The laggards constitute a transitional category between the clear success of Achievers/Middlers and the virtually nil capacity of the Marginals.

Among the laggards, two states Maharashtra and Uttar Pradesh are late bloomers, but now adding capacity at a good pace (Maharashtra could potentially break into the Middler category). Others such as Punjab and Odisha seem set to lag for the foreseeable future.

Finding a clear pattern of factors turns out to be challenging. Land corresponds most strongly with laggard status, with all six states having land challenges. Power deficits are also moderate or high in five of these states.

Other than these partial trends, no particular combination of factors stands out. State-level factors may be doing as much or more of the explanatory work in this category, as the Maharashtra case study suggests (see below).

4.4. Pathways to marginal status: Poor Discom health, land challenges, low coal costs

Seven states are Marginals, the category with extremely low solar installed and pipeline capacity. Unlike Middlers and Laggards, several clear patterns can be detected in our data to identify pathways to poor performance.

None of the Marginals are associated with more than three favorable factors. All Marginals also have poor Discom health and major land challenges. Some are densely populated such as West Bengal and Kerala, while others such as Jharkhand and Assam are tribal dominated (tribal land has special protections under Indian law). Four of the seven states (namely Bihar, Jharkhand, West Bengal and Assam) also lie in or near India's coal-rich belt which makes coal much more competitive.

This adds up to a picture in which the majority of the five factors are unfavorable for each Marginal state. Moreover, none of the Marginals show anomalous behavior. A deeper dive into specific states would doubtlessly reveal additional local factors. For example, literature on West Bengal indicates the influence of the coal lobby and initial leadership in offgrid solar that diverged from national priorities [32], but it appears that macro factors are sufficiently unfavorable to retard serious progress.

Whereas the top and bottom tier states show clearer patterns for our hypothesized factors, it is difficult to discern a clear common story that binds those in the middle, and local factors could be important for all categories of performance. The three case studies that follow – Karnataka (Achiever), Madhya (Middler) and Maharashtra (Laggard) will bring into sharp relief the complex journey that each state has pursued in its solar quest.

5. Case studies

After having analyzed the likely impact of hypothesized factors on state performance on solar scale-up and proposed possible pathways to levels of performance, we now explore three states in more detail through qualitative process-tracing [27]. These were Karnataka (Achiever), Madhya Pradesh (Middler), and Maharashtra (Laggard). The three are among India's large states, together accounting for 20% of the nation's population and nearly 25% of its area.

Our case studies are based on existing literature, government data, and on-site interviews conducted between late 2018 and early 2020 of about 25 experts from government, industry, and consultancies (see Appendix B: List of Interviewees). Interviews provide crucial information that we might have missed in our aggregated data analysis and can reveal the salience of state-specific factors.

Our findings indicate that state-specific factors were key determinants (along with the national-level factors common to all states) of these three states' performance. It is likely that this conclusion extends to other major states. Thus, a complete understanding of a state's performance in solar can only be arrived at through a composite analysis combining the two levels.

5.1. Achiever Karnataka

Karnataka is India's eighth largest state in terms of population, sixth largest in area, and seventh largest electricity market in the country. It has a large farming population (accounting for more than 35% of the state's electricity demand) but also hosts the highly globalized information technology center of Bangalore. While the wealthier southern and coastal regions of the state are fertile and well-irrigated, the central and northern portions are poorer and drought affected, but also receive

[3] Interview #24. See Appendix A.

[4] There was reportedly high rent-seeking activity in the Tamil Nadu solar story, though this was challenging to confirm or disprove.

excellent solar irradiance. This regional divide is also a key characteristic of the state's electricity sector [33].

Karnataka is far from India's major coalfields. It does have large hydropower resources (about 5 GW), but their performance is dependent on the intensity of monsoon rainfall.

Our factor-based approach above would point toward Karnataka reaching a Middler, perhaps even an Achiever status, given several favorable factors, with land as a serious barrier. However Karnataka was, as of September 2019, India's best performing state in utility-scale solar capacity (Fig. 1) with an installed capacity of 6.5 GW (and another 1.233 GW in the pipeline). Our findings point to political and bureaucratic leadership, some of it unintended, as key additional factors.

Karnataka was a late arrival to the solar story. Though being the first southern state to issue its solar policy (in 2011), capacity additions lagged for several years. The 2014 update to its solar policy committed to 1.6 GW of utility-scale solar by 2021 [34]. Its initially modest solar targets were increased to 6 GW in early 2017 [35].

Of our six factors analyzed above, Karnataka has three coded as favorable (Fig. 4), with the fourth (land access) assessed as unfavorable. Also note that, though Discom health was favorable as averaged over the 2015–19 period, Karnataka's Discoms were not healthy until 2016 (see Appendix A, Fig. 2).

Our interviewees indicated that high power deficit (persistent through 2016) was the biggest driver behind the state's solar push.[5] High coal costs were also a key factor.[6] Land acquisition was however the biggest challenge.[7] The state government does not own large tracts of contiguous land, and there is a history of strong, organized farmer movements in Karnataka. Intra-state grid quality was a concern in only 10% of the state.[8]

Karnataka's solar success was a product of both careful energy planning and populist politics. The state's energy minister D. K. Shivakumar of the then-ruling Congress Party and the senior energy bureaucrat, P. Ravikumar, were in charge. They first decided that practically all the solar electricity generated would be for in-state consumption.[9] This was an approach that positioned solar to solve domestic power challenges, rather than earning revenue through out-of-state export. The bureaucrat was given full autonomy by the energy minister to design policy specifics.[10]

The linchpin of the strategy was a massive 13,000-acre Pavagada solar park with a targeted capacity of 2.05 GW, located in the poor and drought-affected district of Tumakuru. A major barrier to the construction of a major solar park in the state was land, in spite of its poor productivity, with farmers extremely reluctant to sell.[11] Moreover, conversion of agricultural land to non-agricultural uses was not easy under land laws dating back to the 1960s. (These laws were appropriately designed to protect small farmers from powerful landed interests at the time.) The stringent conversion process was relaxed through an amendment by the state government in 2014 [36].

The Pavagada model involved leasing land rather than acquiring it outright. The leases were long-term (28 years). Rather than a single lump sum, farmers got a recurring, annual payment of 21,000 Indian Rupees per acre per year,[12] escalated by 5% every two years. At the end of the lease period the land will be returned to its owners with an additional amount to compensate for land degradation. Intense engagement with farmers every two weeks was undertaken to convince them of the new model, ably led by the former state renewable energy agency chief G V Balaram.[13] Still, negotiations took more than a year.[14] The first leases were signed in January 2016, and construction of the park began in April of that year with a deadline of core infrastructure by February 2017.[15]

The first auctions were held in April 2016 with tariffs close to Rs. 4.80 (7.3 cents) per kWh. These were mainly central government-driven. However, the central government pulled back from its commitment to a part of the tendering at which point the state government took the lead and completed all auctions.[16] More than 60% of the final installed capacity at Pavagada has been achieved through state auctions [37].

Pavagada was however not Karnataka's only means to achieve solar success. Close to 70% of the state's utility-scale capacity has been achieved through an innovative semi-distributed model [38]. In this approach, 20 MW capacity per project was auctioned at the level of sub-district level geographic units, known as talukas.[17] This semi-distributed solar model emerged not so much from energy planning as out of a populist politics of energy minister Shivakumar to disburse spending widely across all parts of the state, including its more remote rural areas.[18] The tariffs discovered were relatively high.[19]

To summarize, two of our national-level factors–power deficits, high coal costs–triggered the state's search for solar. Solar irradiance was highly favorable. Discom health was a challenge initially but improved after 2016 and aided the process. But these drivers, by themselves, were insufficient. Success was additionally determined through the exercise of local leadership, with the top politician and bureaucrat in the energy ministry working closely together.[20]

This leadership overcame barriers through innovative land-leasing and semi-distributed models. It closely monitored and took charge of the auctions process after facing delays from the central government. Redistributionist politics indirectly achieved an even greater level of installed capacity than the state's flagship solar park by pioneering a semi-distributed capacity model at sub-district scales. Whereas national-level factors would lead us to expect an above-average performance, Karnataka raced to the very top of the league due to these local factors.

5.2. *Middler Madhya Pradesh*

Madhya Pradesh is India's fifth largest state in terms of population, second largest in area, and fifth largest electricity market in the country. Farming dominates this state's employment, with agriculture accounting for about 40% of the state's electricity demand. It is a poorer state with widespread energy poverty [40]. It is also weakly industrialized and globalized, though agricultural productivity has grown strongly in recent years. The eastern part of the state is adjacent to India's coal belt.

Our factor coding points to Madhya Pradesh likely being a Laggard, given its unfavorable factors on many fronts, though with land as favorable. However it ranks as a Middler. As discussed below, our findings point to inter-state competition and leadership as key additional factors in play.

The state began its solar journey early, under the then-chief minister (the highest elected official of an Indian state) Shivraj Singh Chauhan.

[5] Interviews #1, #3, #4, #6.
[6] Interviews #1, #3, #6, #7, #8.
[7] Interviews #1, #3, #6.
[8] Interview #6.
[9] Interview #6.
[10] Interview #6.
[11] Interview #1.
[12] This is approximately $285 at current exchange rates.
[13] Interviews #3, #5.
[14] Interviews #3, #6.
[15] Interview #3.
[16] Interview #3.
[17] Karnataka has approximately 230 talukas.
[18] Interview #6.
[19] E.g. above Rs. 3 (4.7 cents) per kWh in a major auction in February 2018 [39]. In comparison, record low tariffs had been achieved in auctions in Rewa, Madhya Pradesh (Rs. 3.30 in February 2017) and Bhadla, Rajasthan (Rs.2.62 in May 2017).
[20] Though the party in power in the state (Congress Party) was not aligned to Modi's party (Bharatiya Janata Party) running the central government during the period under study, this did not emerge as a factor.

Chauhan reportedly attempted to compete with Gujarat's then-chief minister Narendra Modi's high capacity additions in the 2009–12 period [31].[21] In 2011, the state announced plans to issue a major 200 MW solar tender. This led to the completion in 2014 of a 151 MW plant in Neemuch, at the time India's largest single solar project. The state issued its solar policy in 2012 [41], and pushed for 1.4 GW capacity by 2015 [42]. It had achieved an impressive 936 MW installed capacity by early 2015, the beginning point of our study [43].

As of September 2019, Madhya Pradesh had a utility-scale installed solar capacity of 1.927 GW, with an additional 0.202 GW in the pipeline, ranking sixth in the country (Fig. 1). This is a large but not massive number. But it has increased steadily over time, and continues to do so. In terms of our national-level drivers, the state had three key factors as favorable, namely irradiance, land, and coal costs, whereas Discom health and power deficits were unfavorable.

Madhya Pradesh's biggest contribution to solar leadership was the innovative approach it took for a major solar park near the city of Rewa, with an installed capacity of 750 MW. The leadership of Manu Shrivastava, a senior state energy bureaucrat, was crucial.[22] The Rewa auction, held in February of 2017, was state-driven rather than central government driven. It achieved a breakthrough tariff of Rs. 3.30 per kWh (over the lifetime of the contract), 24% below the previous lowest bid in the Indian market, opening the door for an even greater acceleration of solar capacity nationwide.

But the significance of Rewa was beyond the tariff breakthrough it achieved. First, the low tariff itself was a result of several factors. Financing was available from the World Bank at a low interest rate of 0.25%. An innovative payment guarantee to project developers was also designed that greatly protected them against offtaker risk. It consisted of three layers – a letter of credit, a payment security fund, and a signed guarantee against default by the state government. This alleviated the Discom health barrier and raised investor confidence [44].[23] The auctioning process was also open and transparent.

Another new element in Rewa was an open access contract, with 24% of generation committed to powering metro rail services in the national capital New Delhi. The remaining 76% was for in-state use. Some of these approaches were not aligned with central government requirements for subsidies, so Madhya Pradesh decided to forgo the subsidies.[24]

Madhya Pradesh's solar pathway has not been free from twists and turns, however. The state government temporarily withdrew solar's must-run status in 2017, but then restored it after criticism. It also rescinded its earlier policies of waiving transmission charges for solar [46]. Currently, although some coal plants are being shut down, others (more efficient) are also being built.[25]

Madhya Pradesh's poor Discom health and low power deficits did not favor strong solar performance. Though its coal costs are ranked as being "moderate," they just missed being classified as "low" (Fig. 4). In fact, thermal plants in the east of the state have access to plenty of cheap coal, being adjacent to major coalfields. This really leaves land availability as the only strongly positive motivator – 80% of land for the Rewa solar park, for instance, was provided by the state government.[26] But there are multiple, non-energy uses of government-owned land in any state. Based on these criteria, it would be reasonable to expect the state to have been a Laggard or worse in solar performance. In fact, it performed well beyond what national-level factors indicate.

Several factors, most of them local, explain this trajectory. The early start in solar was likely motivated by the political factor of intra-party competition, outlined above. Continuing success with initiatives such as Rewa was partly driven by positioning solar as an export commodity that could earn revenues.[27] The factor of individual leadership, in this case with the senior renewable energy bureaucrat playing a key role, was crucial. Finally, the role of international institutions (specifically, the World Bank) facilitated lower costs and raised investor confidence. All these factors came together, along with good land availability, to put Madhya Pradesh on India's solar leadership map.

5.3. Laggard Maharashtra

Maharashtra is India's second largest state in terms of population, third largest in area, and the largest electricity market in the country. Economically, it is a prosperous state with strong industrialization and urbanization in its western portions with globalized cities such as Mumbai (India's financial capital) and Pune. But Maharashtra is also a massive state with large parts of its hinterland being poorer and drought affected. A large portion of the population is dependent on agriculture accounting for nearly 31% of the state's electricity demand.

Maharashtra might well have been a Middler based on our coding, though power deficits were low, and, like Karnataka, land was a major barrier. However, it finished in the Laggard category. Our findings point to the importance of path-dependence and interest groups in addition to land as key reasons.

To understand its story, it is important to note that Maharashtra has not lagged in renewables more broadly, with the nation's highest cogeneration capacity and ranking consistently among the top three wind generators in the country for over a decade. Maharashtra also has India's largest rooftop solar capacity. Overall, the state ranked fourth in the country in net renewables capacity in March 2020 [47]. However, Maharashtra was a late starter on utility-scale solar. Its solar policy was issued as late as 2015, with a target of 7.5 GW to be achieved by 2019 [48]. Actual capacity has fallen well short of this. As of September 2019, Maharashtra had an installed utility-scale solar capacity of 1.474 GW, and a pipeline of 2.075 GW. A large fraction of this capacity was installed only in the previous two years (the comparable figure in September 2017 was 378 MW). Given the massive size of the state's electricity market, this performance is low and slow.

Why couldn't Maharashtra replicate its earlier success in wind, cogeneration, and rooftop solar in the utility-scale segment? Examination of factor data (Fig. 4) reveals that the state is coded low for power deficits[28] and land availability, and moderate on Discom health and coal costs [49]. Thus, two of the four most impactful factors are favorable for solar scale-up.

A notable feature of Maharashtra's solar story is its lack of successful solar parks, which distinguishes it from our other two case studies. Land has historically been difficult to acquire in the state and farmers are well-organized.[29] A tragic suicide in January 2018 of an 84-year old farmer Dharma Patil protesting acquisition of his land was a further setback to the state's plans [50]. The land was to be used for the 500 MW state-led Dondaicha solar park in the district of Dhule. The suicide forced the government to scale back its plans for the park, though auctions were ultimately conducted in 2019 for half the original capacity [51]. Dondaicha was one of three larger (500 MW) solar parks planned in the state. The other two were private ventures, one of which was

[21] At the time, both Modi and Chauhan were seen as potential leaders of the BJP for the upcoming national election in 2014. Interviews # 24, #26.

[22] Interviews #18, #26.

[23] Interview #11.

[24] Additionally, Madhya Pradesh also extended contractual innovations to the rooftop segment, using a combination of demand aggregation, reduction of information asymmetry, and subsidies to achieve a low tariff [45].

[25] Interview #10.

[26] Interview #11.

[27] Interview #11.

[28] However, the state went through a serious power deficit period until 2014, largely due to a botched and expensive deal it signed with the Enron Corporation which reportedly involved major rent-seeking activity. Enron was subsequently found guilty of malpractice and fraud in the United States.

[29] Interviews #13, #14.

exposed as a case of criminal fraud, while the other is yet to take off [52].

Counteracting the failure of the solar parks is the hope provided by the innovative concept of solar agricultural feeders. The idea, first conceived by Prayas, a leading energy NGO in the state, involves semi-distributed solar capacity buildouts of up to 50 MW each across numerous rural districts [53–55]. However, unlike Karnataka's semi-distributed approach, this capacity is intended for power feeders dedicated to agricultural use. This promises to reduce agricultural subsidies by more than 30% and ease pressure on groundwater usage. The first tender under this scheme (for a net 750 MW capacity) was undersubscribed and was therefore reissued in June 2019 [56]. The next phase of 1.35 GW capacity was also postponed from 2019 to 2020 due to impending elections [57].

Maharashtra has emerged as a demand center for solar, with currently 4.5 GW currently contracted by its Discom, most of which is from outside the state. Rather than generating its own solar electricity, Maharashtra intends to buy large quantities of cheaper electricity from solar parks in Gujarat and Rajasthan. Intra-state grid congestion has not been a challenge in the state.[30]

There is circumstantial evidence of a degree of bias among Maharashtra's policymakers against utility-scale solar. This is largely a product of the state's history in renewable energy. Maharashtra's large wind and cogeneration capacities were built up after 2004 through energetic lobbying by a major wind manufacturer and the state's powerful sugar industry respectively. The latter has dominated its electoral politics for decades until recently [49]. The state took the feed-in-tariff (FiT) route for both, with tariffs fixed at levels higher than those from many domestic coal-driven plants. Wind persisted on a FiT regime for a long time.[31] The result was a bias toward these interest groups.[32] This path-dependence led to a sustained bias in the state's tariff structures in favor of wind and cogeneration [58]. Utility-scale solar, which was fragmented and lacked a comparable in-state lobby, has always found itself at a disadvantage.[33]

Going purely by national-level structural factors examined earlier, Maharashtra could reasonably be expected to be a Middler state. Its actual performance is however in the Laggard category - a result of a several state-specific factors that detracted from its potential. Land was unquestionably a major barrier. But unlike Karnataka, Maharashtra failed to show leadership to overcome the land challenge. In fact, the leadership was broadly not favorable toward utility-scale solar, with interest group politics and path-dependence driving this reluctance. Strong political alignment with the center did not seem to have made much difference to its solar preferences. However, more recently the state has innovated a promising solar scheme focused on agriculture, the impact of which can only be gauged in the coming months.

6. Implications for Indian federalism and its clean energy transition

India's electricity reform story has always been hugely about state-level dynamics. States have found differing pathways to development both in centralized and more fragmented political eras in the country's history since independence. The Modi era however has been marked by a strong centralization push, and therefore we expected high central government ambitions to be more influential in determining state clean energy outcomes [1].

However, this is not borne out by our analysis. While ambitious central targets (and policies that followed) undoubtedly raised the quantum of installed capacity beyond what would otherwise have turned out, states took very different pathways irrespective of political alignment with the center. In some aligned states such as Madhya Pradesh, central subsidies were rejected in favor of policy alignment with international agencies. In other aligned states such as Maharashtra, utility-scale solar was emphasized only tentatively and late. In opposition-run Karnataka however, solar was pushed strongly – but for internal reasons and to satisfy internal demands. States also served as sites of autonomous experimentation in clean energy - Karnataka's approach to land aggregation, Madhya Pradesh's early positioning of solar as an export commodity, and Maharashtra's agriculture solar scheme are exemplars. Inter-state competition (Gujarat and Madhya Pradesh, Andhra Pradesh and Telangana) has also served to accelerate solar adoption.

This is not to say the central government did not matter. We see a clear role for central government tenders in helping solar-rich Rajasthan, for example, overcome problems with its weak Discom by leading the tender process. The UDAY scheme to bailout the troubled Discoms may have created space for states to pursue solar scale-up if they wanted to.

The legacy of the Discoms' weak financial health – a central challenge in India's clean energy story - looms larger now, particularly as demand was soft even before COVID-19 crisis, which made many Discoms reluctant to buy additional power when they were already running existing coal power plants at low plant loads and yet still were legally obligated to compensate coal plants [1]. The COVID crisis has accentuated these problems, weakening power demand further and exacerbating Discom finance. Moreover, solar supply chains and the solar labor force have been disrupted by the outbreak, slowing the pace of implementation of large solar projects with the long-term effects as yet unknown.

Recent proposals to amend the country's foundational electricity statute have raised concerns of a severe erosion of federalism in the sector [59]. At one level this has the potential to achieve hard-to-do tasks such as Discom solvency (though UDAY's failure is not a good sign), contract enforcement, and more rational tariff structures. At another level however, spaces for state-level experimentation and innovation could also shrink, triggering greater center-state conflict that could damage India's foundational democratic principles and internal cohesion.

Could policy overcome the biggest barriers to solar ramp-up we have identified? Although this question takes us outside the scope of this study, some answers are suggested by our findings. The factors we identified with the most influence – land access, Discom health, and coal costs are key (in addition to state-specific measures at the local level). For instance, when it comes to land, creative solutions, such as floating solar arrays on bodies of water, increased pursuit of rooftop solar, or installing panels above roadways and medians, might be useful if costs can be controlled. And, innovative leasing models, such as the one Karnataka adopted, could be utilized by other agriculture-heavy states such as Maharashtra.

Overcoming the serious barrier of the Discom financial crisis is harder, and several attempts by the central government to do so have failed. Solutions will likely involve more use of solar feeders like the one in Maharashtra which would reduce the financial burden from subsidized electricity for farmers. Any resolution that leads to more solar deployment will ultimately require a reckoning with India's coal sector. This is a sector that employs many people, particularly in the east, where other opportunities are limited. The country's towering air pollution problems provide additional impetus for finding a transition from coal, though the current government's plans to open new domestic coal mines suggests that is a way's off.

Electricity reform in India is about balancing clean energy and energy poverty/access imperatives, which are often, but not always, in alignment. The interface between central preferences and state imperatives is a rich site for future research that can further clarify how India could overcome these twin challenges in its developmental journey. Future studies might use optimized power system scenarios to get at the

[30] Interviews #13, #14.
[31] Interviews #14, #18.
[32] Interviews #17, #18, #24.
[33] Interviews #14, #17.

right mix of energy sources to balance the load with as much renewable energy as possible.

The challenges of fostering clean energy in India, as many environmentally minded international observers want, go well beyond whether the central government is supportive. To assess the prospects for successful long-run scale-up of renewables, we have to surface these state-level barriers and opportunities. The central government's target of 100 GW of installed solar capacity by 2022 was always a stretch goal and even if it only reaches 65 GW, as is currently projected, that will be an achievement nonetheless [60]. What is clear is that if India collectively is to scale up solar specifically and renewables writ large, analysts and policymakers will have to have a better appreciation of the challenges in India's states and how to overcome them. That lesson is important not just for India but for other federal systems as well as large developing countries seeking to advance coherent energy policies across a broad and varied geography [61]. Whether countries like India can navigate these challenges will be important for the world as we collectively address the common threat of climate change.

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.

Acknowledgments

The authors wish to acknowledge the assistance of Balawant Joshi and M. U. Krishnajith of Idam Infrastructure Ltd for facilitating some of the data collection and Matthew Preisser for assistance in computing irradiance data. We also wish to thank the LBJ School of Public Affairs and the IC^2 Institute at the University of Texas-Austin for supporting this research.

Appendix A:. Methodology for factor coding

In this appendix, we lay out the details of how each of the factors – solar irradiance, power deficits, Discom financial health, coal costs, land access, grid congestion, and political alignment - were analyzed to determine a final assessment for the states under consideration. Since each factor is very different, its measures were normalized to a common qualitative ranking to facilitate cross-factor comparison presented in the main text of the paper. The presentation is organized for each factor in terms of the four categories of installed solar capacity, Achievers, Middlers, Laggards, and Marginals.

Solar irradiance

The intensity of solar radiation is among the most important factors that we expect to influence levels of scale-up. This is a purely physical measure of the solar resource, dependent on the latitude and weather patterns of a state. Since practically all utility-scale solar installations in India are of the photovoltaic (PV) type, the relevant parameter is Global Horizontal Irradiance (GHI), typically expressed in units of kWh/m^2/day.

We used the National Renewable Energy Laboratory's National Solar Radiation Database (NSRDB) as our data source to rank states based on solar irradiance levels (NREL, 2014). GHI varies at every geographical

Classification	State	Averaged GHI (kWh/m2/day)	Assessment
Achievers	Karnataka	5.69	Very High
	Andhra Pradesh	5.56	Very High
	Telangana	5.53	Very High
	Rajasthan	5.53	Very High
Middlers	Tamil Nadu	5.76	Very High
	Madhya Pradesh	5.38	High
	Gujarat	5.58	Very High
Laggards	Uttarakhand	5.01	High
	Punjab	5.01	High
	Odisha	5.23	High
	Maharashtra	5.52	Very High
	Chhattisgarh	5.33	High
	Uttar Pradesh	5.13	High
Marginals	Bihar	5.05	High
	Assam	4.61	Moderate
	Kerala	5.46	High
	Jharkhand	5.21	High
	West Bengal	4.96	Moderate
	Haryana	5.14	High

Fig. A1. Statewise averaged Global Horizontal Irradiance (GHI_{avg}) in kWh/m^2/day. Source – NREL, 2014.

Classification	STATE	Energy (2015)	Peak (2015)	Energy (2016)	Peak (2016)	Energy (2017)	Peak (2017)	Energy (2018)	Peak (2018)	Average Energy Balance	Average Peak Balance	Final Assessment
Achievers	Karnataka	-4.3	-4.5	-5.2	-6.8	-0.5	-0.2	-0.2	-0.5	**-2.6**	**-3.0**	High
	Andhra Pradesh	-4.9	-5.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1	**-1.3**	-1.3	Moderate
	Telangana*	-6.2	-14.3	-0.6	-0.1	0.0	0	-0.1	-0.1	**-1.7**	**-3.6**	High
	Rajasthan	-0.6	0.0	-0.3	0.0	-0.6	-2.5	-0.8	-1.3	-0.6	-1.0	Low
Middlers	Tamil Nadu	-3.1	-1.5	-0.7	-0.1	0.0	0.0	-0.2	-0.2	**-1.0**	-0.5	Moderate
	Madhya Pradesh	-0.5	-0.4	0.0	0.0	0.0	-0.1	0	-0.3	-0.1	-0.2	Low
	Gujarat	0.0	-0.8	0.0	-0.3	0.0	0.0	0	0	0.0	-0.3	Low
Laggards	Uttarakhand	-3.0	0.0	-1.7	0.0	-0.6	0.0	-0.2	0	**-1.4**	0.0	Moderate
	Punjab	-1.0	-13.1	0.0	0.0	0.0	0	0	0	-0.3	**-3.3**	Moderate
	Odisha	-1.6	-0.7	-0.6	0.0	0.0	0.0	-0.3	-5.4	-0.6	**-1.5**	Moderate
	Maharashtra	-1.3	-1.7	-0.3	-1.8	0.0	-1.4	-0.2	-0.2	-0.5	-1.3	Low
	Chhattisgarh	-1.3	-4.7	-1.3	-4.5	-0.2	-0.6	-0.3	-6.8	**-0.8**	**-4.2**	High
	Uttar Pradesh	-15.6	-17.0	-12.5	-14.6	-1.7	-6.2	-1.5	-10.9	**-7.8**	**-12.2**	High
Marginals	Bihar	-2.8	-4.0	-1.3	-6.7	-2.3	-3.2	-1.5	-0.1	**-2.0**	**-3.5**	High
	Assam	-7.0	-13.3	-5.6	-7.6	-3.6	-2.4	-3.5	-4.2	**-4.9**	**-6.9**	High
	Kerala	-1.5	-4.4	-0.5	-3.1	-0.2	-3.3	-0.4	-0.6	-0.7	**-2.9**	Moderate
	Jharkhand	-2.8	-1.9	-2.3	0.0	-0.7	0.0	-1.9	-5.4	**-1.9**	**-1.8**	High
	West Bengal	-0.6	-0.3	-0.3	-0.3	-0.3	-0.6	-0.4	-0.3	-0.4	-0.4	Low
	Haryana	-0.4	0.0	-0.1	0.0	0.0	0.0	0	-1.4	-0.1	-0.4	Low

Fig. A2. Power supply deficit assessment for states. Values above median in bold font. Sources – Central Electricity Authority, 2016, 2017, 2018, 2019.

point, and a value for each state was obtained by averaging over all grid points in our dataset, called GHI_{avg}. The resultant values were then assigned to qualitative rankings as follows - $GHI_{avg} \geq 5.5$ = Very High, $5.0 \leq GHI_{avg} < 5.5$ = High, $4.5 \leq GHI_{avg} < 5.0$ = Moderate.

Power deficits

Data for deficits in energy (kWh) and peak power (MW) for each of the states under study is listed in Fig. A1 for the financial year 2014–15 to 2017–18. The deficits are expressed as a percentage of the demand for that year.

For each state, the deficits were first averaged over all the years in question. Median values were calculated for the averages. Thus, half the states lay above the median and the other half below, by definition. The states were then assessed as High, Moderate, or Low based on where they stood with respect to the median values of energy and power. If

Classification	State	2015	2016	2017	2018
Achievers	Karnataka	B+/B+/B/B/C+	A/A/A/B+/B	A/A/A/B+/B	A/B+/B+/B/B
	Andhra Pradesh	B+/B+	B+/B	A/B+	A/B+
	Telangana	B+/B	A/B+	B+/B+	B+/B+
	Rajasthan	B/C+/C+	C+/C+/C+	B/C+/C+	B/B/B
Middlers	Tamil Nadu	B	C+	B	B
	Madhya Pradesh	B+/B/B	B/B/B	B+/B/C+	B+/C+/C+
	Gujarat	A+/A+/A+/A+	A+/A+/A+/A	A+/A+/A+/A+	A+/A+/A+/A+
Laggards	Uttarakhand	A	A	A+	A+
	Punjab	A+	B+	B+	B+
	Maharashtra	A	B+	A	B+
	Chhattisgarh	B+	B+	B	B
	Uttar Pradesh	B/C+/C+/C+/C	B/C+/C+/C/C	C+/C+/C/C/C	B/C/C/C/C
Marginals	Bihar	B+/B	B+/B	B+/B	B+/B
	Assam	B	B	B	B
	Kerala	B	B+	B+	B
	Jharkhand	C	C	C	C
	West Bengal	B+	B+	B	B+
	Haryana	B/B	C+/C+	B/B	B+/B+

Fig. A3. State distribution company ratings according to the Indian government. Sources – Ministry of Power, 2015, 2016, 2017, 2018.

Assessment	Averaged Score
Very High	> 9.5
High	8.6 to 9.5
Moderate	7.6 to 8.5
Subpar	6.6 to 7.5
Low	5.6 to 6.5
Very Low	5 to 5.5

Fig. A4. Mapping numerical scores to qualitative assessments of distribution company health.

both were above the medians for each, the state was scored as High. If both were lower, a Low score was assigned. A Moderate score corresponded with only one of energy and power being higher than the median value.

Discom health

The Power Finance Corporation (a state agency affiliated with the Indian Ministry of Power known by its acronym PFC) issues ratings (denoted as letter grades) for distribution company health for states annually. These ratings are presented in Fig. A2 for the years 2015–18. Some states have multiple Discoms, therefore they have multiple letter grades listed. In a few states, the central government leads solar auctions making Discom health less relevant as a factor for performance – this is tabulated in the last column. Discoms in Odisha are in private hands and not assessed by the PFC, and therefore not listed in Fig. A2. PFC defines these grades as follows - A+ = Very High, A = High, B+ = Moderate, B = Below Average, C+ = Low, C = Very Low.

To compare where a state stood relative to each other over the time period tabulated (and in some cases, over its multiple Discoms), the letter grades were first converted to numerical values as follows – A+ = 10, A = 9, B+ = 8, B = 7, C+ = 6, C = 5. The numerical values were then averaged over the time period and Discoms (as applicable). The resultant scores (rounded off to the first decimal place) were finally converted to qualitative assessments. These were, in increasing order of Discom health - Very Poor, Poor, Subpar, Moderate, Good, and Very Good. Fig. A3 shows how the numerical ranges were mapped on to these qualitative assessments. The final results are shown in Fig. A4.

Coal costs

About 90% of the coal used in Indian power plants is from domestic sources. Coal costs for India's thermal power stations vary hugely by state, and even locations within a state. Power plants located close to coal mine pitheads generally pay less for coal compared to plants located further away. Since India's coal belts are predominantly in the east and east-central parts of the country, eastern and central states tend to have lower coal costs than states deeper in the south, west and northwest (Fig A5).

Coal is shipped from mines to plants predominantly by rail, and the cost of transport is a large part of the landed cost of domestic coal at a power plant, sometimes exceeding 50%. Thus, rail transport costs are an acceptable proxy of the variation in the cost of fuel for coal-powered plants.

The data below on coal transport costs (in Indian Rupees per kWh generated) is based on a report from Brookings India. The values for each state are not weighted values over all coal plants in the state, but representative values from a single coal plant. The exact weighted value for any given day will also depend on Plant Load Factors (PLF) for that

Classification	State	2015	2016	2017	2018	Average Score	Assessment
Achievers	Karnataka	5.8	8.4	8.4	7.8	7.6	Moderate
	Andhra Pradesh	8.0	7.5	8.5	8.5	8.1	Moderate
	Telangana	7.5	8.5	8.0	8.0	8.0	Moderate
	Rajasthan	6.3	6.0	6.3	7.0	6.4	Poor
Middlers	Tamil Nadu	7.0	6.0	7.0	6.0	6.5	Poor
	Madhya Pradesh	7.3	7.0	7.0	6.7	7.0	Subpar
	Gujarat	10.0	10.0	10.0	10.0	10.0	Very Good
Laggards	Uttarakhand	9.0	9.0	10.0	10.0	9.5	Good
	Punjab	10.0	8.0	8.0	8.0	8.5	Moderate
	Maharashtra	9.0	8.0	9.0	8.0	8.5	Moderate
	Chhattisgarh	8.0	8.0	7.0	7.0	7.5	Subpar
	Uttar Pradesh	6.0	5.8	5.4	5.4	5.7	Poor
Marginals	Bihar	7.5	7.5	7.5	7.5	7.5	Subpar
	Assam	7.0	7.0	7.0	7.0	7.0	Subpar
	Kerala	7.0	8.0	8.0	7.0	7.5	Subpar
	Jharkhand	5.0	5.0	5.0	5.0	5.0	Very Poor
	West Bengal	8.0	8.0	7.0	8.0	7.8	Moderate
	Haryana	7.0	6.0	7.0	8.0	7.0	Subpar

Fig. A5. Final qualitative assessments of distribution company (Discom) health for Indian states.

Classification	STATE	Coal Transport Cost Rupees/kWh	Coal Transport Cost
Achievers	Karnataka	1.16	Moderate
	Andhra Pradesh	1.59	High
	Telangana	0.13	Low
	Rajasthan	1.47	High
Middlers	Tamil Nadu	2.10	High
	Madhya Pradesh	0.86	Moderate
	Gujarat	1.67	High
Laggards	Uttarakhand	N/A	High*
	Punjab	1.71	High
	Odisha	0.28	Low
	Maharashtra	1.01	Moderate
	Chhattisgarh	0.65	Low
	Uttar Pradesh	1.41	High
Marginals	Bihar	0.49	Low
	Delhi	1.41	High
	Assam	N/A	N/A
	Kerala	N/A	High*
	Jharkhand	0.30	Low
	West Bengal	0.75	Low
	Haryana	1.62	High

Fig. A6. Coal transport costs for key states and associated qualitative assessments. (* indicates value deduced from neighboring states.) Source – Kamboj & Tongia, 2018.

day. Thus, our coal data is an approximation of the "true" transport costs. It is likely more accurate for geographically smaller states such as Haryana or Jharkhand, less so for large states with an east–west spread such as Maharashtra.

The data were converted to qualitative assessments in increasing order of costs, namely Low, Moderate, and High. This was determined by first calculating the median of the data (1.09). The range was then divided approximately into three equal slabs centered on the median as follows – <0.85 Rupees/kWh was taken as Low, between 0.85 and 1.35 was Moderate, and >1.35 was High. An inspection of the final assessments is consistent with the expectation of lower coal transport costs in eastern and east-central Indian states, given their proximity to coal mines.

Land access

Land is increasingly a critical issue for scaling-up utility-scale solar capacity. With close to 60% of the population dependent on agriculture, arable land is scarce in India. Wasteland does exist in appreciable quantities in some states, but developers prefer to set up projects on arable or semi-arable land as they want access to grid and other infrastructure.

Land is also among the most challenging factors to find reliable data for. A national "land availability" database for solar projects is not available. Land is a state subject under the Indian constitution, and land records are notoriously opaque, and often maintained in regional languages. A move to collect and store this data in a digital, accessible format is underway but has shown variable progress in states.

Considering the constraints, we assessed this factor by conducting a poll of project developers in combination with what our interviewees said. Several developers were reluctant to share their views on land availability as they considered it strategic information, but four did respond to our poll, of which three responses were relevant. In addition, our interviewees provided us useful pointers – for example, high barriers on land acquisition and conversion in states with large fractions of indigenous tribes such as Jharkhand, Odisha, Chhattisgarh, Assam and others. In very few cases (such as Telangana) there was a contradiction between project polling and interviewee responses, in which case we chose the more pessimistic assessment. The final land access assessment is shown in Fig. A6, denoted as Low or Moderate. Note than none of the respondents scored "High" for land in any state, reflecting the fact that access to land is at least somewhat challenging in each of the Indian states considered in this study.

Grid congestion (Intra-state)

Grid congestion is potentially a significant barrier for solar scale-up. India has reported on high levels of curtailment in the past, most prominently in the state of Tamil Nadu. Congestion can occur both at intra-state and inter-state levels. The "Green Corridors" initiative is aimed to ease inter-state grid congestion. In this study, we consider only the intra-state barriers. This is because much of the evacuation problem exists at the local level. It is also consistent with the objective of the study, which is to understand why some states have done better than

Classification	State	Land Access
Achievers	Karnataka	Low
	Andhra Pradesh	Low
	Telangana	Moderate
	Rajasthan	Moderate
Middlers	Tamil Nadu	Low
	Madhya Pradesh	Moderate
	Gujarat	Moderate
Laggards	Uttarakhand	N/A
	Punjab	N/A
	Odisha	Low
	Maharashtra	Low
	Chhattisgarh	Low
	Uttar Pradesh	Low
Marginals	Bihar	Low
	Delhi	Low
	Assam	Low
	Kerala	Low
	Jharkhand	Low
	West Bengal	Low
	Haryana	Low

Fig. A7. Land access assessment for utility-scale solar projects in states. Source – Idam Infrastructure (2019).

others in scaling up utility-scale solar. If inter-state evacuation is lacking, then it is difficult to ascribe that to any particular state; also the Green Corridors project is primarily a central government responsibility.

Intra-state grid congestion occurs at local scales and is also a dynamic factor that can change from minute to minute. However, three metrics can help us identify states in which such congestion may be higher in a structural sense. The first is the intra-state grid capacity, data for which is available from state transmission companies. The second is any judicial trail on curtailment for a state. The third is an exhaustive search of media reports on grid congestion.

Fig. A7 lists these metrics and relevant sources. The ratio between total intra-state grid capacity and installed power capacity (renewable and non-renewable) is calculated for each state and listed in the "capacity ratio" column. A ratio of 2 or below is assessed as having potential for grid congestion within the state. Additional sources indicating any past incidents of grid congestion are listed in the right-most column. The final assessment is a combination of both, if either indicates congestion, then the factor is assessed as a "yes." Otherwise, the assessment is "Not Detected," as the lack of evidence is not a guarantee that grid congestion has not occurred in these states.

Political alignment

The final factor considered was political alignment, i.e. a case of the state government being aligned with the party in control of the central government. During the period 2015–19, this was Prime Minister Modi's Bharatiya Janata Party (BJP) in the center, the dominant party in a ruling coalition of a few other smaller parties. The ruling alliance is known as the National Democratic Alliance.

The test for political alignment was as follows. If the state in question was governed by the BJP or its formal ally within the NDA during the entire or almost entire period of interest, then the factor was coded as "High." Otherwise, it was coded as "Low." If there was a mixed alignment during the time period (for example due to an intermediate election or a change of government in the state), then the coding was

Classification	State	Intra-state Grid Capacity (MVA)	Installed Generation Capacity (MW)	Capacity Ratio	Grid Congestion Assessment	Additional Sources
Achievers	Karnataka	56,496	28,162	2.0	Yes	Prateek (2019), Khurana (2016), Jai (2016)
	Andhra Pradesh	31,388	24,391	1.3	Yes	Khurana (2016)
	Telangana	52,127	15,832	3.3	None Detected	
	Rajasthan	82,216	22,912	3.6	Yes	Mercom (2019), Seetharaman & Chandrasekaran (2019)
Middlers	Tamil Nadu	61,821	31,519	2.0	Yes	CERC (2016), Jai (2016), Sengupta (2016), Vijayakumar (2019)
	Madhya Pradesh	56,034	23,531	2.4	None Detected	
	Gujarat	110,047	32,632	3.4	Yes	Vora (2019), Mercom (2019)
Laggards	Uttarakhand	8,438	3,405	2.5	None Detected	
	Punjab	33,566	13,432	2.5	None Detected	
	Odisha	18,069	7,655	2.4	None Detected	
	Maharashtra	123,847	44,149	2.8	None Detected	
	Chhattisgarh	14,467	14,044	1.0	Yes	
	Uttar Pradesh	89,012	25,215	3.5	Yes	APTEL (2015)
Marginals	Bihar	18,230	4,568	4.0	None Detected	
	Assam	6,158	1,714	3.6	None Detected	
	Kerala	17,548	5085.0	3.5	Yes	Saur Energy (2019)
	Jharkhand	5,655	1,775	3.2	Yes	Interview 23, Khurana (2016)
	West Bengal	29,883	10,581	2.8	None Detected	
	Haryana	41,715	11,275	3.7	None Detected	

Fig. A8. Statewise grid congestion assessment. Sources – Respective state transmission company websites and others (listed in last column.)

Classification	State	Political Alignment
Achievers	Karnataka	Low
	Andhra Pradesh	High
	Telangana	Low
	Rajasthan	High
Middlers	Tamil Nadu	Low
	Madhya Pradesh	High
	Gujarat	High
Laggards	Uttarakhand	High
	Punjab	Moderate
	Odisha	Low
	Maharashtra	High
	Chhattisgarh	High
	Uttar Pradesh	Moderate
Marginals	Bihar	Moderate
	Delhi	Low
	Assam	Moderate
	Kerala	Low
	Jharkhand	High
	West Bengal	Low
	Haryana	High

Fig. A9. Assessment of states' political alignment with the central government.

Classification	State	Auctions Led By
Achievers	Karnataka	State
	Andhra Pradesh	Center
	Telangana	State
	Rajasthan	Center
Middlers	Tamil Nadu	State
	Madhya Pradesh	State
	Gujarat	State
Laggards	Uttarakhand	State
	Punjab	State
	Odisha	Center
	Maharashtra	State
	Chhattisgarh	Both
	Uttar Pradesh	State
Marginals	Bihar	State
	Assam	N/A
	Kerala	Center
	Jharkhand	Center
	West Bengal	State
	Haryana	Both

Fig. A10. Leading level of government for solar auctions. Source: Bridge to India, September 2019.

"Moderate." The results are shown in Fig. A8.

Central vs state auctions

In addition to the factors above, used for more rigorous testing of association with solar performance, we also denoted states in which solar auctions were mainly centrally led. This classification was used as a filter, for example during case study selection. In general, states in which central-led auctions dominated are less a reflection of the state's success in scale-up (though not entirely, as land acquisition for example is still a major responsibility of the state) (Figs. A9 and A10).

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Appendix B: List of Interviewees

Karnataka

1. Senior manager in state government renewables agency, November 2018
2. Senior official in state government electricity agency, November 2018
3. Senior official in state government renewables agency, November 2018
4. Senior manager in state electricity regulator, November 2018
5. Senior managers in state electricity regulator, November 2018
6. Senior bureaucrat in state government, November 2018
7. Senior manager in regional electricity agency, November 2018
8. Senior manager in central government electricity agency, November 2018

Madhya Pradesh

9. Private sector consultant, January 2019
10. Senior bureaucrat in state government, January 2019
11. Senior bureaucrat in state government, January 2019
12. Manager in solar project development firm, January 2019

Maharashtra

13. Senior bureaucrat in state government, January 2019
14. Former state electricity regulator, February 2019
15. Senior manager in state generating company, December 2018
16. Senior manager in energy think tank, February 2019
17. Former program director at energy think tank, May 2020

National

18. CEO of energy policy consulting firm, November 2017
19. Director at major power generation firm, November 2017, January 2019
20. Senior manager at major power generation firm, November 2017, January 2019
21. Former senior official at intergovernmental organization, November 2017
22. Former senior central government electricity regulator, April 2019
23. Energy journalist, November 2018
25. Senior manager at energy policy consulting firm, August 2018
26. Energy journalist, February 2019

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