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It's Always Sunny in India (?): An empirical, state-level analysis of the growth of solar power in India

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Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:
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India has set ambitious targets for solar power deployment, a central element in its low-carbon energy transition. However, the feasibility of reaching these targets has not been systematically studied. This thesis assesses the feasibility of India's solar targets for 2022 and 2030 by quantitatively mapping the trajectories of solar power growth both nationally and at the state level using logistic and Gompertz growth models fitted to historical data. A set of deductive hypotheses are formulated to investigate why some states deployed solar PV earlier than others, and if late adopters benefited from the experience of early adopters. Existing growth trends are used to assess the feasibility of the national and state-level solar targets.

The thesis finds that besides abundant solar resources, the extent of solar deployment in states was influenced by favorable business environments and competitiveness with respect to thermal power. Except for Karnataka, India and its states are not on track to achieve their targets. Growth appears to be slowing nationally due to retardation in states with the highest deployment levels and most of India's solar potential. While later adopters had shorter transition durations, they did not always achieve faster rates due to less favorable conditions. This signals the need to focus on interventions that reaccelerate growth while simultaneously expanding deployment in lagging states.

Keywords: utility-scale solar power, solar in India, energy transition, technology diffusion, growth models, feasibility

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-Avi

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List of Abbreviation

AP Andhra Pradesh
AS Assam
BR Bihar
CEA Central Electricity Authority
CT Chhattisgarh
CUF Capacity utilization factor
DISCOM Distribution company
EBD Ease of Doing Business
FIT Feed-in tariff
GDP Gross Domestic Product
GHG Greenhouse gas
GHI Global Horizontal Irradiance
GJ Gujarat
GST Goods and Services Tax
GW Gigawatt
GWh Gigawatt hour
IAM Integrated Assessment Model
IEA International Energy Agency
INR Indian National Rupee
IPCC Intergovernmental Panel on Climate Change
JH Jharkhand
JN-NSM Jawaharlal Nehru National Solar Mission
KA Karnataka
kWh Kilowatt hour
MH Maharashtra
MNRE Ministry of New and Renewable Energy
MP Madhya Pradesh
MW Megawatt
OECD Organization for Economic Cooperation and Development
OD Odisha
PB Punjab
PV Photovoltaic
R&D Research and development
REC Renewable Energy Certificate
RJ Rajasthan
RPO Renewable Purchase Obligation
TN Tamil Nadu
TS Telangana
TW Terawatt
TWh Terawatt hour
UP Uttar Pradesh
UT Union territory
WB West Bengal

Chapter 1: Introduction

India is home to over 1.35 billion people, making it the world's second most populous country and fifth largest economy (World Bank 2021). It is expected to surpass China and become the world's most populous country and second largest economy by mid-century (OECD 2018) – this growth has major implications for the country's future energy needs. India's energy demand has doubled in the last 20 years, and as its share in the global primary energy demand expands to 9.2%, it will drive about 25% of the increase in global primary energy demand between 2019-2040 (IEA 2021). To cater to this demand, India will need to supplement its existing electricity generation capacity with 'a power system the size of the European Union' over the next two decades (IEA 2021). Given its heavy reliance on fossil fuels, fulfilling its increasing energy demand also contributes to driving up its greenhouse gas (GHG) emissions. While India's per capita GHG emissions are less than half the global average, it is the world's fourth largest emitter today with nearly 70% of its power being coal-generated (World Bank 2021; IEA 2020a).This means that India needs solutions that allow it to radically expand its electricity generation while simultaneously reducing GHG emissions to mitigate the risk of dangerous climate change.

One such solution may be renewable power. There is growing global consensus on the importance of the rapid, large-scale deployment of renewable energy in order to reduce GHG emissions from energy-generation, and restrict the rise in mean surface temperatures to (ideally) below 1.5°C (IPCC 2018). Photovoltaic (PV) solar has emerged as the poster child of this transition to low-carbon energy, with its cumulative installed capacity exploding from 5 GW in 2005 to 710 GW in 2020 globally, and global annual capacity additions exceeding 100 GW in both 2019 and 2020 (IEA 2020).

India committed to increase the share of renewable energy sources to 40% of its total installed power generation capacity at the Paris COP in 2015. In addition, the Indian government also set an ambitious target to install 175 GW of renewable energy generation capacity by 2022 (NITI Aayog 2015), and 450 GW by 2030 (Lakshman 2019). Solar power is at the heart of these pledges, with the Indian government targeting to install 100 GW of grid-connected solar PV under the Jawaharlal Nehru National Solar Mission (JN-NSM) by 2022 – this includes 60 GW of large-scale, ground-mounted and 40 GW of small-scale, roof-top units distributed across the country's 28 states and eight union territories (MNRE 2015). Moreover, in line with its global climate leadership aspirations, India co-launched the International Solar Alliance alongside France in 2015, and has since expressed 'soft' (aspirational) targets to further scale-up its grid-connected solar power capacity to 200 GW by 2027 and 300 GW by 2030 (CEA 2018; 2019).

As of 31 March 2021, the total installed grid-connected solar capacity in India was 40.1 GW – this is remarkable growth from a measly 161 MW in 2010. However, the annual capacity additions at both the national and state levels ever since the launch of the JN-NSM have consistently failed to meet annual targets, with roof-top solar performing especially poorly. These failures have been attributed to various infrastructural, institutional, and financial constraints (Hairat and Ghosh 2017). Despite these shortfalls, one Indian minister claimed that India was "on-track to comfortably achieve" the 2022 target and another went so far as to say they would be met "before the stipulated time" (Economic Times 2018; Business Standard 2018).

Given the level of deployment today, India needs to install over 60 GW of solar capacity – 1.5 times what it has now - in a period of one year to meet its JN-NSM target. Further, it will have to add another 100 GW by 2027, and an additional 100 GW by 2030 if it chooses to pursue its soft targets. This effectively means a growth of 650% over the coming decade. Does the ongoing growth trajectory for solar power in India suggest this is feasible?

1.2. Problem definition

The literature on India's renewable energy transition, including research on the growth of solar power in the country, has focused on national-level policies such as the JN-NSM (Behuria 2020; Shidore and Busby 2019; Raina and Sinha 2019; Rohankar *et al.* 2016), or the economics of solar power generation (Sindhu *et al.* 2017; Yenneti 2016; Lu *et al.* 2020). However, this literature does not systematically address the question of the feasibility of India's solar targets. In particular, there is a dearth of literature that has empirically studied and quantitatively measured the growth of solar power in India. This task is complicated because the growth of new technologies is not linear. According to classic technology diffusion studies, the growth trajectory of a new technology is S-shaped – it initially accelerates, achieves a point of maximum growth, and eventually slows and reaches saturation (Griliches 1957; Rogers 2003; Grubler 1996). Given that accelerating growth is imperative to the achievement of the JN-NSM targets, it is worth determining if growth indeed continues to accelerate in different states and at the national level. In this thesis I will analyze the compatibility of the JN-NSM targets with actual growth trajectories and maximum growth rates attained along the national and state-specific S-curves to both, evaluate the feasibility of achieving them and estimate the growth rates required to get there.

The second insight from the technology diffusion literature is that the adoption of new technologies is spatially uneven. The literature highlights diffusion of technology from 'core' to 'periphery' as well as the possibility that late adopters benefit from the experience of early adopters, and are thus able to deploy a technology more rapidly (Hägerstrand 1967; Grubler 1990; Wilson *et al.* 2013). India is highly spatially heterogenous. It consists of 28 states and eight UTs with different natural conditions and varying levels of economic development. Understanding how a new technology such as solar power diffuses in such systems is critical for understanding the feasibility of solar targets. Yet, there has been considerably less attention to the state-level in the literature; the few studies at the sub-national level either only study a small sample of states (Sareen and Kale 2018), or analyze the performance and impacts of particular solar projects. Notable exceptions include Shrimali *et al.* (2020), and Busby and Shidore (2021). The immense internal diversity of India, and the sheer magnitude of its system demand a more granular yet expansive analysis with a sub-national focus.

The research comparing the level of solar deployment between different Indian states and untangling the factors underlying them (Busby and Shidore 2021; Shrimali *et al.* 2020)remains limited in its temporal focus. Given the heterogeneity between states, it is worth investigating why some states adopted the technology earlier than others and if late adopters in India have indeed benefitted from their pioneering peers.

1.2. Aim and research questions

In an endeavor to address these gaps, the aim of this thesis is to perform an empirical, granular analysis of the growth of solar power in India. It seeks to understand how different states have contributed to this growth, and quantitatively measure the gap between the observed growth and the growth that is required to fulfil the national and state-level JN-NSM and other targets. I do this by answering the following questions:

1. What are the trajectories and quantitative parameters for the growth of solar power nationally and in different states in India?
2. Why did some Indian states deploy solar PV earlier than others, and are there significant differences between early and late adopters?
3. Given the existing trends and patterns of growth, can India and its states be expected to meet the JN-NSM targets?
4. What can be done to accelerate the deployment of solar power in India?

1.3. Scope and delimitations

A conceptual limitation of this thesis is that it extrapolates knowledge based on past experience to future developments. While it exerts maximum care to adhere to rigorous analysis and known causal mechanisms of solar power diffusion, it is not impossible that radically new and unforeseen developments can either accelerate or slow down solar power in India as compared to what is projected by this thesis. To study these unforeseen events and processes, a deeper and more granular analysis of the state of the solar power sector in India would be needed – something which was not possible in this thesis due to time and resource limitations. Additionally, the analysis in this thesis is limited to utility-scale, grid-connected solar PV, and does not analyze the growth of smaller-scale, rooftop or off-grid, decentralized solar PV.

This thesis initially set out to analyze the growth of solar power in each of India's 28 states and eight Union Territories (UTs). However, it was found that 16 had small power systems generating <10 TWh of electricity annually. Of the 20 remaining states, three others lacked significant utility-scale solar PV deployment, leaving 17 states that were finally analyzed. The 17 states considered accounted for 99% of India's total installed solar capacity in March 2021. The exclusion criteria and their respective justifications are explicitly outlined in Chapter 3.

1.4. Disposition of this thesis

The rest of this thesis is structured as follows. *Chapter 2* discusses the existing literature pertaining to technology diffusion, feasibility, and solar power in India. *Chapter 3* draws on insights from the literature to elaborate on the theories and methods used to address the research questions. *Chapter*

4 systematically presents the results and findings from the analyses. *Chapter 5* presents a comprehensive discussion of the results and situates the findings within the context of the aim of this thesis and the research questions it poses. Finally, *Chapter 6* concludes the thesis by highlighting its key findings, makings recommendations for policymakers, and briefly listing its implications for future action and investigation.

Chapter 2: Literature Review

This literature review consists of three parts. The first section comprehensively describes the intellectual history of key concepts and theories in technology diffusion studies. The second section defines the concept of feasibility in the technology diffusion context, and lastly, the third section offers an exhaustive review of the literature covering the growth of solar power in India.

2.1. How does technology diffusion work?

There is a rich literature spanning multiple disciplines and taking various perspectives on the transitions of and in energy systems. Historically, the evolution of national energy transitions has involved three types of changes – a change in energy flows coordinated through energy markets, a change in the technologies used to extract, transform, and use energy, and a change in the policies that regulate the social and political aspects of energy systems (Cherp *et al.* 2018).

2.1.1. The three perspectives on energy transitions

Cherp *et al.* (2018) argue that national energy transitions occur as a result of the "co-evolution" of three distinct but inter-linked system types viz. techno-economic systems, socio-technical systems, and systems of political actions; each of these system types is the focus of a distinct "perspective" on national energy transitions, which constitutes a field of scholarship with its own concepts, theories, variables and disciplinary roots.

The techno-economic perspective on energy transitions focuses on energy systems described by energy flow, and the production and consumption of energy coordinated through energy markets. Its disciplinary roots lie in different streams of economics including neoclassical, natural resource, engineering, ecological and evolutionary economics. It also derives insights from economic history. It approaches the study of energy transitions by focusing on energy resources, supply-demand dynamics, and prices, and uses market equilibria, supply-demand balance, resource depletion, population and economic growth, as well as demand convergence to explain the evolution of energy systems. Given its quantitative nature, it also involves the development of quantitative energy models which can be used to create long-term scenarios for the evolution of energy systems under different assumptions; these models were later coupled with Earth system models to created more complex Integrated Assessment Models (IAMs) which have since been at the heart of a growing demand for urgent action against climate change. However, this perspective does not fully explain the mechanisms underlying energy transitions because it fails to account for technological innovation and diffusion, as well as the origins and dynamics of policies.

The socio-technical perspective draws from the knowledge of science and technology studies, the sociology of technology, and evolutionary economics. This perspective studies transitions through the lens of socio-technical regimes, niches, and innovation systems. It utilizes the concepts of technology lock-in, path-dependence, regime resilience and destabilization, niche innovation and learning, and technology diffusion to explain the evolution of socio-technical systems. Opposed to the techno-economic perspective, it takes a more "complex and nuanced view of technology as a social phenomenon". The shortfalls of this perspective include a lack of focus on (i) changes in existing technologies that do not undergo significant innovation, (ii) the decline of old technologies, (iii) distinction from the techno-economic and political systems.

The political perspective on energy systems focuses on policymaking as the primary driver of energy transitions. It draws on various threads from within political science – policy studies, international relations, political economy – to study the evolution of energy systems through states, their interests and preferences, larger coalitions and paradigms. It utilizes various concepts and theories to explain the mechanisms underlying the transitions of energy systems. These include the ideas of state autonomy, increasing returns, and multiple-streams, as well as the advocacy coalition framework and other policy diffusion theories. A shortcoming of this perspective is a general lack of engagement with the dynamics and economics of technologies.

The diversity of the ideas within these three perspectives demonstrate that there can be a multitude of mechanisms driving a country's energy transition. For example, more affluent countries with larger economies may have the ability to allocate greater resources to support the development of new technologies and be more attractive to investors (Jewell 2011; Schaffer and Bernauer 2014). While countries undergoing faster growth in energy demand may also be motivated to develop alternate technologies and attract investments, countries that are resource-rich in terms of energy sources may lack the motivation and/or capacity to develop low-carbon technologies (Cherp *et al.* 2017; Colgan 2014). The fossil fuel subsidies in energy-exporting countries may also negatively impact the profitability of renewables (Jewell *et al.* 2018). It has also been argued that democracy is tied to better climate policy outcomes and greater political incentives in favor of policies that support renewables such as feed-in tariffs (Böhmelt *et al.* 2016; Bayer and Urpelainen 2016). Thus, it is important to view a transition through different analytical lenses in order to understand its drivers and dynamics more comprehensively.

2.1.2. The S-curve and technology diffusion

Griliches (1957) pioneered the study of technology diffusion with his investigation of the uptake of hybrid corn varieties in the states within the United States and the differences induced due to the timing of adoption. This was followed by Rogers (2003), who developed the first systematic theory for the diffusion of innovations in a social system. Together, they laid the foundations for the study of energy transitions by conceptualizing how the processes of technological development, innovation, and diffusion drive the adoption of a technology over time and across space. They also pioneered the idea that the adoption of a new technology in a system (or the technology lifecycle) can be modelled using an S-shaped curve – the S-curve of technology diffusion.

The technology adoption literature has identified that the S-curve of technology diffusion is composed of three distinct phases viz. the formative, growth, and saturation phases (Jacobsson and Johnson 2000; Markard 2018). The introduction of a technology marks the start of the formative phase where the technology begins to slowly take root, facing resistance in the form of high costs and uncertainty (Bento *et al.* 2018). This phase is characterized by slow, erratic growth that builds up towards a point where the formation of socio-technical regimes allows the technology to enter a phase of steady growth (Napp *et al.* 2017; Markard 2018; Rotmans *et al.* 2001). This point of technology 'takeoff' signals the end of the formative phase and the beginning of the growth phase, where the technology undergoes accelerated expansion, benefitting from "increasing returns" due to rising profitability, increasing technological learning and maturing policy support (Arthur and Arrow 1994; Pierson 2000). The growth of the technology continues to accelerate until it reaches a maxima or inflection point, after which growth begins to slow down in the face of socio-technical, techno-economic, and political constraints. These constraints can take the form of rising marginal costs, challenges associated with integration into the existing system, geophysical limitations, political and/or social resistance (Markard 2018; Blazquez *et al.* 2018; Kramer and Haigh 2009; Wüstenhagen *et al.* 2007). Finally, the technology reaches a stage where it undergoes no further growth and achieves its maximum market share – the saturation phase (Grubler 1996, Rotmans *et al.* 2001).

Hägenstrand (1967) pioneered the idea that the diffusion of innovation is not only a temporal, but also a spatial process. Grubler (1990) extended the idea of spatial diffusion to technology adoption, leading to the development of the concept that technology spreads from an innovation 'core' to the 'rim', and then on to the 'periphery'. This added another dimension to the study of technology diffusion, and set the stage for a larger debate on the impact of the timing of adoption on its growth characteristics.

2.1.3. The early versus late-adopter debate

Griliches (1957) seminal work on the adoption of hybrid corn revealed that states which adopted the new corn varieties earlier also adopted it faster. This result was amongst the first prompts for a much larger debate on the impact of early/late adoption on the diffusion of a technology. Marchetti (1983) presented a competing hypothesis, arguing that later adopters adopt a technology faster as they benefit from the experience and learning of earlier adopters. Grubler (1990) presented a similar argument in his study of the diffusion of various infrastructures, which was followed by several studies which also argued that technology adoption was faster (shorter transition durations) in systems at the 'rim' as opposed to the 'periphery' (Wilson *et al.* 2013, Wilson and Grubler 2011). However, there have also been studies that report the contrary, arguing that the speed of diffusion is not influenced by the timing of adoption (e.g. Dekimpe *et al.* 1998).

It has been particularly difficult to conclusively evaluate the impact of adoption timing in case of later-adopters given that these systems are still undergoing transition, and that their duration of transition cannot be reliably computed (Wilson *et al.* 2013; Lund 2006). A number of studies have argued that factors such as a slower transfer of global knowledge, higher capital costs, and lower institutional capacity may have negatively impacted the speed of technology in late adopters (Bento *et al.* 2018; Gallagher 2006; Gosens *et al.* 2017; Steffen *et al.* 2018; Huenteler *et al.* 2016). This argument is linked to the earlier findings of Griliches (1957), Marchetti (1983), and Grubler (1990) who also suggested that relatively poorer adoption environments may have led to lower technology penetration in case of late adopters.

The question of the degree to which a technology penetrates into the system is important, especially when dealing with the adoption of low-carbon energy technologies in the context of climate change mitigation. Linking this question to the timing of adoption (early vs late) poses analytical challenges as it is difficult to measure the saturation levels of technologies that are still in transition, and thus the literature has turned to measuring the growth rates of renewables with respect to the size of energy systems instead. Gosens *et al.* (2017) analysed the growth rates of wind and solar power in all countries globally and found that while early adopters benefited from the experience of technology front-runners, in the case of later adopters (especially developing countries), the learning benefits were cancelled out by their larger socio-economic and institutional constraints. Other studies in the field of economics have also argued that technology adoption occurs both later and slower in developing countries (Comin and Hobijn 2004; Comin and Mestieri 2018).

2.1.4. Measuring technological growth

As the previous sub-section elaborates, how growth is measured is central to answering questions about the extent of technology diffusion. Typically, transition speeds have been measured using specific market-share thresholds, with 1%, 10% initial shares and 50%, 90% post-transition shares being the commonly used thresholds in the literature (Grubler *et al.* 2016). Grubler (1990) found that technological change follows non-linear, S-shaped curves that have been popular in the technology diffusion literature. He demonstrates that given the characteristics of the logistic function (which generates a symmetric S-curve), the time taken for the share to change from 1% to 50% and from 50% to 99% is the same as the time it takes to grow from 10% to 90% of the market share. This property was used to define the duration of transition (Δt), which has since become the most commonly used metric for the measurement of technological growth. However, there has been criticism that Δt does not take into account the extent to which a technology penetrates into a system. Moreover, it fares especially poorly when measuring growth in case of countries experiencing growth spurts or where technologies are still undergoing growth. In this backdrop, Cherp *et al.* (forthcoming) have proposed an alternate metric to measure technological growth – G (see more in Chapter 3).

The question of measurement is especially important in order to understand how fast technologies move through the technology adoption cycle and how adoption can be accelerated in the context of action against climate change. Bento *et al.* (2018) analyzed the temporal and spatial dynamics of the growth of energy technologies, with an emphasis on measuring the durations of their respective formative phases. There has also been a growing body of work specifically connecting the energy transition literature to the climate targets (e.g. Wilson *et al.* 2013). Thus, the focus then becomes analyzing if it is feasible for low-carbon energy technologies to diffuse fast enough to prevent dangerous anthropogenic climate change, and achieve the climate targets that have been set for this purpose.

2.2. The feasibility question

Determining the feasibility of an outcome depends on imagining the future within the constraints of the reality of our times. Current research on the future of the climate targets depends on Integrated Assessment Models (IAMs) that connect assumptions about economic, energy, and geophysical systems to create pathways to reduce global emissions and mitigate dangerous climate change. Predominantly techno-economic in their outlook, IAMs do a good job of ruling out pathways that are technologically and economically infeasible, but the negation of this infeasibility does not correspond to what is feasible in the real world (Riahi *et al.* 2015). The real world is much more complex than what these complex models assume, and the difference between what is theoretically possible and that which is practically feasible is decided by social and political constraints. Jewell and Cherp (2020) suggest that the feasibility of any pathway is constrained by techno-economic, socio-technical, and political systems which Cherp *et al.* (2018) had identified as being the drivers of energy transitions. Though their primary focus is on the political aspect of feasibility, they break the question of feasibility into three parts – feasibility of what, when and where, and for whom? Following a comprehensive analysis of the evolution of different technologies in various contexts they argue that the most obvious method to assess the feasibility of climate action is to look at what has been accomplished in the past, since these actions are more likely to be replicated in the future; as contexts evolve, the capabilities of actors rise, costs fall, and barriers diminish, a greater number of countries will be able to follow in the lead of the pioneers.

In the more specific context of new energy technologies, feasibility relates to the rates at which they move through the technology lifecycle and achieve greater market penetration. Climate targets at the global as well as national scales invariably call for the rapid deployment of low-carbon technologies to decarbonize the energy system and radically reduce emissions. In the case of these technologies, the assessment of the feasibility of deployment scenarios and pathways is done by comparing the growth required to what has been historically observed in various parts of the world (Wilson *et al.* 2013).

However, most of the technology diffusion literature has focused on OECD and other industrialized countries, leaving significant gaps in knowledge about the dynamics of technology adoption in the developing world. Consequently, there has also been a lack of literature on the feasibility aspects of rapid renewables deployment in developing nations. One such nation that occupies a particularly important position in the global order due to its sheer size and impact is India.

2.3. What do we know about solar power in India?

2.2.1. The story of solar power in India thus far

By virtue of its geography, India receives an average of eight hours of sunlight a day and about 300 sunny days per year with a daily average solar insolation of 4-7 kWh/m^2 (Mahtta *et al.* 2014) In their analysis of solar potential hotspots in India, Ramachandra *et al.* (2011) characterized 58% of the country's total land area as being "exceptionally" suited to commercial utilization of energy and highlighted their potential value towards power generation and emission reduction in the Indian context.

On conducting a geospatial and techno-economic analysis of solar resources in India, Deshmukh *et al.* (2019) estimate the country has a cumulative solar potential between 1300-5200 GW for utility-scale solar PV. They suggest that even the lower end of this estimate, if realized, would be nearly equivalent to India's projected energy demand for 2030.

Figure 1 illustrates the geographical distribution of India's solar resource expressed in the form of its global horizontal irradiance (GHI).

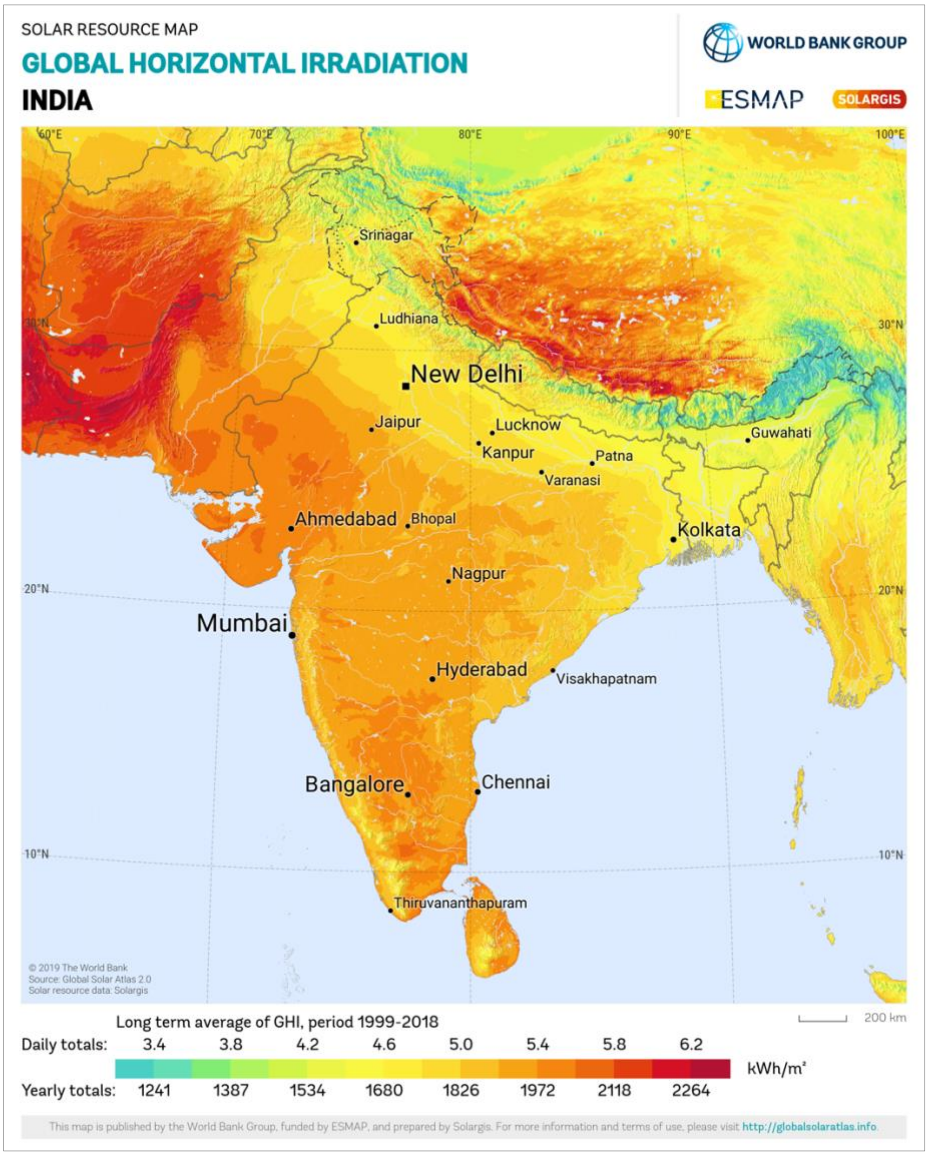

Figure 1. India's global horizontal solar irradiance (Global Solar Atlas 2021).

This potential has not gone unnoticed by the Indian government, which has initiated a wide bouquet of measures to incentivize the growth of a solar power sector in the country. The Jawaharlal Nehru National Solar Mission (JN-NSM) launched in 2010 was the country's first major initiative to catalyze the growth of solar power in the country. Under the aegis of the National Action Plan on Climate Change, it aimed to place India at the forefront of the solar energy arena globally, establish an environment that nurtured the growth of the erstwhile expensive technology to grid parity by 2022 domestically, and simultaneously address national energy security challenges (MNRE 2011). India's solar energy sector was "virtually non-existent" when the JN-NSM was launched with an aim to install 20 GW of grid-connected and 2 GW of off-grid solar power by 2022 (Quitzow 2015).

Narendra Modi, the erstwhile chief minister of the state of Gujarat, was elected Prime Minister of India in 2014. Shidore and Busby (2019) argue that this was a turning point for the solar power sector in India. Modi was amongst the first Indian politicians to embrace solar power, and as chief minister of Gujarat, oversaw several initiatives that pushed the state to pole position in India's solar power sector. Shidore and Busby (2019) posit that Modi's previous experience with the technology and a growing anticipation that it was approaching grid-parity led his government to mount an aggressive, top-down push for more ambitious solar targets nationally. However, they also emphasize that this push was not driven by techno-economic considerations alone.

On further analyzing national policy trends and expert interviews Shidore and Busby (2019) identify four primary drivers of the growth of solar power in India – "*domestic politics, global pressure and partnerships, attracting investment, and energy sovereignty.*" They argue that the push for greater solar deployment was part of a campaign to enhance Modi's image as a modern, pro-development leader. In addition, they suggest that this move also helped India establish stronger ties with the Obama administration in the US and eased pressure on India in the run-up to the Paris COP. Given the appeal of solar as an emerging technology and India's development aspirations, they highlight that the Indian government saw it as an opportunity to "mobilize domestic capital and attract foreign investments". Lastly, they also report the utility of solar power as a means to India securing greater energy sovereignty – an issue that has been a longstanding concern in Indian polity.

In this background, India ratified the Paris Agreement in 2015 and committed to expand the share of renewable power to 40% of its primary electricity production by 2030. Subsequently, the Indian government set a target to install 175 GW of grid-connected renewable power generation capacity by 2022 and revised the solar target under the JN-NSM to this end. It now aims to install 100 GW of grid-connected solar capacity by 2022 with a 60:40 split between utility-scale, ground-mounted and small-scale, rooftop solar PV. These targets were further split and allocated between different states and union territories, many of which formulated their own state solar policies. There is an air of uncertainty around how the 100 GW figure came about. Several experts interviewed by Busby and Shidore (2019) expressed skepticism about the origins of the target with one claiming the number was "pulled from air without much study or analysis". Nonetheless, India further raised its clean energy ambitions by declaring to install 450 GW of renewable energy generation capacity by 2030 at the 2019 Climate Action Summit. In the backdrop of this announcement, the national Central Electricity Authority presented 'soft' targets of raising India's installed solar capacity to 200 GW by 2027 and 300 GW by 2030 (CEA 2018; 2019).

As of March 2021, India's installed solar power capacity stands at 40 GW – about 250 times what it had in 2010 – and it generated over 58 TWh of electricity from the source in 2020-2021 which was larger than Portugal's total power consumption in 2020 (APREN 2021). How did India, a developing country, manage to pull it off? And how does it plan to fulfil its lofty ambitions for the future? The following sub-sections offer a glimpse into how India's energy policy environment has driven its solar transition.

2.2.2 India's solar policy landscape

The JN-NSM was designed as a three-phase process, with successive phases aimed to learn from the experience of their predecessors. The first phase ran from 2010-2013, with a focus on promoting solar thermal power, deploying off-grid systems to meet the energy needs of citizens without access to commercial power, and initiating the installation of grid-connected solar PV. The second phase, which ran from 2013-2017, focused on increasing competition in the Indian solar power sector by pushing for a more dynamic expansion in installed capacity to achieve economies of scale. The third and final phase is currently underway with a target to achieve 100 GW of installed grid-connected solar capacity by 2022. (MNRE 2021)

The Indian government has formulated a set of policy instruments to promote the development of renewable energy in the country which Dasgupta and Sankhyayan (2018) classify into three distinct categories – regulation and standard, quantity instruments, and price instruments (illustrated in Table 1).

Table 1. Policy instruments for renewable energy promotion (adapted from Dasgupta and Sankhyayan 2018).

Types of policy	Regulation and standard	Quantity instruments	Price instruments
Principle	A command and control mechanism where stakeholders are bound to act according to mandates	A market-based mechanism that targets absolute quantity for renewable energy production	A market-based mechanism that creates a favourable price regime for renewable energy and let market determine quantity
Example	• Renewable energy mandates such as building codes • Flexible grid access through net metering	• Renewable Portfolio Standards (RPS)/ Renewable Purchase Obligation (RPO) • Renewable Energy Certificates (REC) • Renewable Regulatory Fund (RRF)	• Fiscal incentive • Feed-in-tariff

In keeping with this framework, the Indian government introduced various schemes and policies with the purpose of creating a financial support system for solar power producers under the umbrella of the JN-NSM. The existing landscape allows developers to sell the power they generate to electricity distribution companies (DISCOMs) at a feed-in-tariff (FIT) or at a rate that is decided through a competitive reverse-bidding process. In addition, they also have the option to directly negotiate a rate with large open-access consumers or trade in Renewable Energy Certificates (RECs) to claim fiscal benefits when they sell to DISCOMs at rates lower than the average purchase cost (Bhowmik 2020). Bose and Sarkar (2019) have noted that the focus of government support has shifted from FITs to competitive bidding as solar power has reached greater market penetration in the country. Developers in the solar power sector were also given tax breaks on excise and customs duties until 2017, which was replaced with a lower Goods and Services Tax (GST) and lower customs. Other policy instruments implemented to support solar power include the Clean Energy Cess, Generation-based Incentives, and Viability Gap Funding (see Rohankar *et al.* 2016, Bhowmik 2020 for detailed reviews).

While all these policies led by the central government give direction to India's solar drive, state-level renewable energy policies such as Accelerated Depreciation, the Renewable Energy Infrastructure Development Fund, miscellaneous charge exemptions, and the individual states' energy policies are crucial for actual ground-level implementation (Rohankar *et al.* 2016).

2.2.3. Looks like a great policy landscape, but…

Despite the remarkable growth in India's solar power capacity, the picture is not all rosy. The complexity of India as a system poses several challenges to the large-scale deployment of the technology on the national scale. Rathore *et al.* (2018) are notable in their analysis of the challenges faced by utility-scale solar in the country. Raina and Sinha (2019) also perform a comprehensive review of India's solar-specific policies and associated challenges.

India is highly spatially heterogenous with tremendous geophysical diversity, and Deshmukh *et al.* (2019) demonstrate how most of India's geographically unevenly distributed solar resource is concentrated in the western and southern regions.

In terms of the technology to harness this resource and convert it into useful energy, Shidore and Busby (2019) highlight how India has relied on importing technology from abroad and fallen behind on the domestic manufacturing and innovation fronts. Behuria (2020) points out that close to 90% of the solar modules used in the country are imported, with belated policies instituted to support domestic manufacturing lacking effect. The inferior performance of the domestically manufactured panels, and a failure to integrate domestic R&D and manufacturing into the JN-NSM as a priority have led to an increasing dependence on foreign imports which runs against the Indian government's stated aim of securing energy sovereignty (Behuria 2020; Rathore *et al.* 2018).

Land acquisition has been another barrier to the growth of solar power in India. Bajaj (2019) demonstrates how acquiring land for large solar projects in India has been a complicated and antagonistic process involving considerable legal gymnastics. Often, the land acquired by solar developers ends up being isolated from power substations and lacks access to the distribution infrastructure – this further impacts the viability of projects due to large transmission & distribution, technical, and commercial losses for developers (Pargal and Banerjee 2014). The water requirements associated with these projects pose another limitation as close to 80% of the solar PV resources are situated in areas that experience high water stress (Deshmukh *et al.* 2019).

The capital-intensive nature of solar projects raises further challenges for project developers. The lack of availability of finance, and loans on favorable terms, along with payment defaults by

DISCOMs in poor health all negatively impact the large-scale deployment of solar power in the country (see Bhowmik 2020 for a comprehensive review).

On a policy level, the lack of a comprehensive solar policy for India raises redundancies in the system with the involvement of multiple bureaucratic institutions complicating regulatory processes, tax and licensing mechanisms (Bhowmik 2020). Project developers need to undergo cumbersome processes and long waits to obtain benefits and subsidies, and market's entry requirements are prohibitive to the arrival of new companies. Rathore *et al.* (2018) and Bhowmik (2020) also highlight the lack of institutional transparency and corruption as barriers to the growth of the sector.

In sum, while the long-term forecasts for the sector remain favorable and promising, there are question marks over the immediate feasibility of achieving the JN-NSM targets from multiple quarters., with Ranjan (2020) predicting India would only be able to install a total 65 GW of solar capacity by 2022. Taxes on solar products, renegotiations of tariffs, cancellation of tenders, shortfalls in domestic R&D, innovation, and manufacturing, as well as issues with grid balancing in the face of supply variability have all been listed as factors responsible for jeopardizing the 2022 targets (Bhowmik 2020; Hairat and Ghosh 2017; Shidore and Busby 2019).

2.2.4. The sub-national picture

The literature cited in this chapter so far has almost exclusively focused on solar power at the national scale. But it's the country's 28 states and 8 union territories that constitute the large, complex system that is India.

Sareen and Kale (2018) performed an analysis of the socio-political dynamics of the development of solar power infrastructure in two states in the western region viz. Gujarat and Rajasthan with a focus on the energy justice elements of the ongoing transition. Yenneti (2016) developed a case study of industrial perception to the FIT policy in the state of Gujarat while (Kuthanazhi *et al.* 2014) studied the deployment of distributed solar PV through local governments in Kerala. Sathapathy *et al.* (2018) investigated the slow uptake of rooftop solar in the state of Odisha. It is evident that all of these studies have a very narrow focus in terms of the number of states they cover – this is a trend that runs through the literature on solar power in India with most research focusing on particular states or projects.

A notable exception in this regard is the work of Shrimali *et al.* (2020), and Busby and Shidore (2021) who attempt more comprehensive, granular analyses of solar power in larger samples of Indian states. Deshmukh *et al.* (2019) also focus on Indian states in their geospatial and techno-economic analysis of India's solar generation potential.

Shrimali *et al.* (2020) perform an econometric analysis of the policy, economic, and structural drivers of solar power in Indian states. They used a panel dataset covering 30 Indian states and UTs over 11 years (2009-2019) and identified that states with higher GDPs, healthier DISCOMs, greater RPOs and dedicated solar parks have greater solar deployment. They argue that wealthier states were better able to afford what was initially an expensive technology and states with more functional DISCOMs were better equipped to deal with the complexities of integrating solar power into the grid. Thus, they predict that when the health of DISCOMs and the affordability of solar power as a technology improve, it would lead to greater adoption of solar power in Indian states. They also find that more stringent RPOs were tied to higher solar deployment and thus advocate for command-and-control policy as an effective means to promoting greater deployment of solar power. Addressing the issues around land acquisition highlighted earlier in the previous sub-section, they point to solar parks as an important driver for solar deployment in Indian states as through them, the government guarantees the availability of land and transmission infrastructure to project developers. They also point out that they find no evidence of the impact of policies such as accelerated depreciation, VGF, net metering and banking of power. However, they concede that evidence may be absent because of data unavailability.

Busby and Shidore (2021) analyze solar deployment in 19 Indian states and categorize them into 4 classes – Achievers, Middlers, Laggards, and Marginals – based on the percentage share of solar power in their respective peak demands. They perform a further analysis to identify factors that influence the level of solar deployment in different states (Table 2). They find that states' solar performance was most linked to higher solar irradiance, healthier DISCOMs, more expensive coal transportation, and greater availability of land. They also find that some characteristics common to states with the best solar performance i.e. the Achievers were a high solar irradiance, good DISCOM health, high coal costs, larger power deficits, and greater land availability. Conversely, states with the worst performance i.e. the Marginals had DISCOMs in bad health, major land availability challenges, and cheap coal. Busby and Shidore (2021) also analyze case studies for Karnataka (Achiever), Madhya Pradesh (Middler), and Maharashtra (Laggard) to identify the dynamics of solar power growth in these states.

Table 2. Classification of states into solar Achievers, Middlers, Laggards, and Marginals (adapted from Busby and Shidore 2021).

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	V 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	V Poor	Low	Low	High
	West Bengal	Moderate	Low	Moderate	Low	Low	Low
	Haryana	High	Low	Subpar	High	Low	High

Busby and Shidore (2021) find that the growth of solar power in Karnataka was driven by high coal transport costs and internal power deficits, and highlight how localized policy was used to circumvent the state's land availability barrier by acquiring land for solar parks through an innovative long-term leasing policy. In case of Madhya Pradesh, solar power growth was driven by intra-party, inter-state competition with Gujarat, as well as targeted local policy that ensured land availability, attracted international finance, and positioned solar power as a revenue-generating export commodity. Maharashtra was flagged as being an underperformer in solar deployment, primarily because of stiff competition with wind power and cogeneration, which have formed strong regimes, a lack of policy impetus to make land acquisition easier amidst low availability, and a tentative approach to utility-scale solar. In conclusion, they argue that while the top-down push from the central government has positively affected solar deployment in India, there has been a good deal of autonomous experimentation within states that has influenced the growth of utility-scale solar in different regions.

2.4. Summary, knowledge gaps, and the focus of this thesis

This literature review exposes the following gaps in the research surrounding the growth of solar power in India. First, there is a dearth of literature that has empirically studied and quantitatively measured the growth of solar power in India using insights about the different phases of the technology lifecycle from the technology diffusion literature. Second, there is a lack of research systematically assessing the feasibility of the JN-NSM and other targets the Indian government has set for 2022 and beyond. Third, relatively less attention has been paid to the growth of solar power at the state-level, with most of the literature either focusing on particular states or projects. Shrimali *et al.* (2020) and Busby and Shidore (2021) are exceptions in that they perform a more comprehensive analysis of the drivers of solar deployment in different Indian states, but their studies lack a temporal focus. In particular, it remains unclear whether the states which adopted solar power later learnt from early adopters and also adopted it faster (meaning that future solar deployment can occur more rapidly). This brings me to the fourth gap, which is a lack of focus on studying the spatial diffusion of solar PV as a technology within India. This thesis contributes to filling these gaps by quantifying the growth of solar power in India nationally and at the state-level, and estimating the growth rates that have been achieved in different states and comparing them against the rates required to meet state and national JN-NSM targets. It will also analyze the spatial diffusion of solar PV among Indian states, investigate the differences in growth characteristics between early and late adopters, and assess which factors influence the growth of solar power in Indian states. Through these analyses, this thesis aims to better explain how solar deployment at the state-level shapes the national picture and suggest what interventions could push India further along its solar growth trajectory.

Chapter 3: Theory and Method

This chapter systematically outlines the theoretical and methodological foundations of this thesis, building on the literature discussed in Chapter 2. It is composed of two separate sections. In the first section, I elaborate on the theory used to (i) model and measure the growth of solar power in Indian states, (ii) study the factors affecting it, and (iii) assess the feasibility of it meeting India's solar deployment targets. The second section describes how the concepts abstracted in the theory are operationalized to answer the research questions posed by this thesis.

3.1. Theory

Pursuing the aim of this thesis involves measuring the growth of solar power in different Indian states and assessing the feasibility of India achieving its solar power capacity installation targets. This section describes the theory that underpins the analytical methods used in this thesis.

3.1.1. Modelling the growth of solar power

The analysis in this thesis relies on representing solar power deployment in India both, nationally and in individual states, as an S-curve. This follows from the larger tradition in the technology diffusion literature that, starting with Griliches (1957), has represented the diffusion of various technologies (from hybrid corn to renewables) as S-shaped curves.

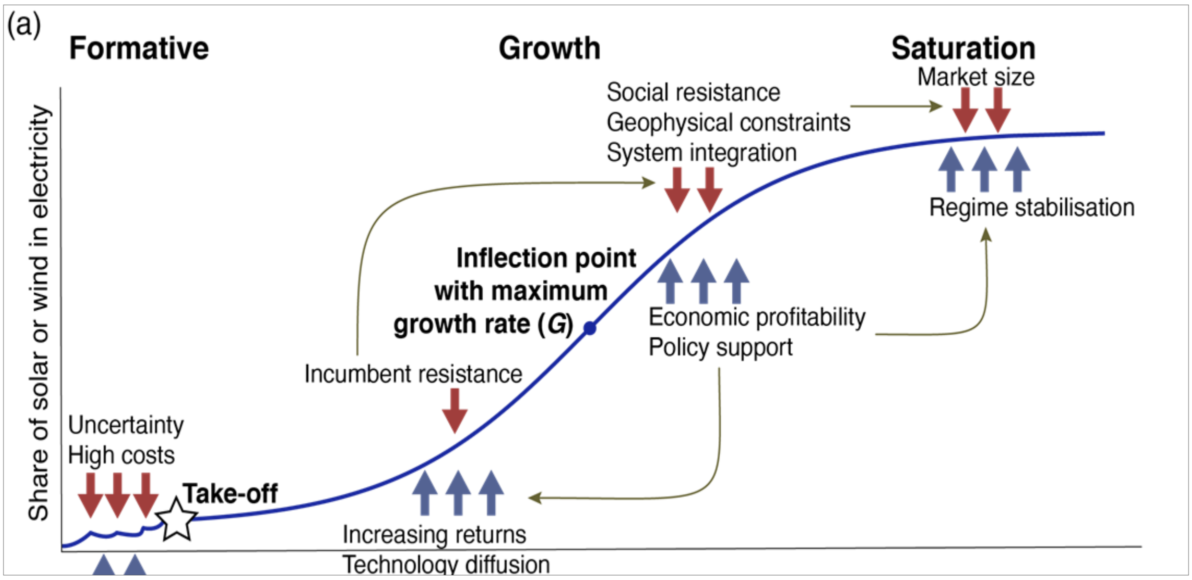

Figure 2. The S-curve of technology diffusion (from Cherp *et al.* forthcoming).

The S-curve of technology adoption has three distinct components viz. the formative, growth, and saturation phases. The mechanisms underlying each of the three phases have been comprehensively discussed in Chapter 2 (section 2.1.2) and briefly highlighted in Figure 2. While the S-curve is a useful conceptual tool, it cannot be used to quantitatively analyze technology growth – doing that requires mathematical growth models.

The logistic curve is the most popularly used growth model in technology diffusion studies. Given that this model presumes symmetry about the inflection point, it is possible to easily calculate the saturation level (or the curve asymptote) once this point has been identified. Despite its popularity, there is a disagreement in the literature over whether the logistic model is the best representation of technology diffusion.

Following Griliches' (1957) seminal work using the logistic curve to model the adoption of hybrid corn in US states, Dixon (1980)demonstrated that the asymmetric Gompertz model offered a more accurate description of the same phenomenon. There is a significant current in the literature that argues in favor of 'skewed' or asymmetric growth curves as being a better representation of technology diffusion. These curves have a longer period of growth after the inflection point, and consequently estimate higher saturation levels and longer transition durations. It has also been argued that such asymmetric models are particularly suited to the diffusion of wind and solar energy technologies (Davies and Diaz-Rainey 2011).

This thesis uses both the logistic and Gompertz models in its analysis of solar power in Indian states. In addition to the two, it also uses a log-linear model, which combines the logistic curve with a linear plot; this hybrid curve is not an S-curve, but it can be used to model technologies that are still in the early phases of the technology lifecycle (Cherp *et al.* forthcoming). Once the adoption of the technology being studied has been mathematically represented through an appropriate growth model, it becomes possible to quantitatively analyze its growth.

3.1.2. How to measure the growth of solar power as a technology?

There are three parameters that characterize the three phases of the S-curve of technology diffusion, which Griliches (1957) has called '*the beginning of the movement, its rate, and its destination'* (Cherp *et al.*, forthcoming). Together, these parameters describe a trajectory of technology adoption which allows for a richer, more dynamic analysis than what is possible through simple comparisons of deployment levels or growth rates at fixed instances of time. In studying the growth of solar power in India, this thesis primarily focuses on the 'beginning' and the 'rate' of its deployment, given that it may be too early to empirically estimate its final 'destination'.

Takeoff – the beginning

In the technology adoption literature, 'takeoff' is a point in the beginning of the S-curve which separates the formative and growth phases; post-takeoff, technology adoption accelerates and undergoes steady expansion. I use this point to mark the *beginning* of solar power's growth phase in a particular system, and also to differentiate between early and late adopters by defining the year in which takeoff is achieved in a system as its 'takeoff year'.

The literature mentions several ways to operationalize the concept of technology takeoff. Historically, while Griliches (1957) used a threshold of 10% of the technology's final penetration level, Rogers (2003) and Marchetti (1983) used threshold values of 2.5% and 10% respectively. More specifically in the case of energy technologies, assuming that neither wind nor solar power would supply 100% of a country's electricity, Bento and Wilson (2016) defined the formative phase to end at 2.5% of the total electricity supply. Cherp *et al.* (forthcoming) use a threshold of 1% (of the total electricity supply) to define takeoff in their analysis. Gosens *et al.* (2017) define their threshold differently, choosing an absolute number (100 MW of installed capacity) instead of using a percentage of the market share.

Thus, while there are several ways to exactly define the threshold, one has to make a larger, conceptual choice between defining it as a percentage of the market share/power supply, or using an absolute threshold value. Though there are advantages to using a percentage share, this thesis follows Gosens *et al.* (2017) and defines an absolute threshold.

In this thesis, solar power is assumed to have achieved "takeoff" in a particular state if the total annual power generated from the source exceeded 500 GWh in any year. This corresponds to approximately 300 MW of installed solar power capacity (assuming an average capacity utilization factor of 18%). I choose to define the threshold in this way to better account for the heterogeneity of system sizes among Indian states – given the large differences between the smaller and larger states, a percentage threshold would not accurately represent the actual extent of solar power deployment. For example, if I were to use the 1% threshold, solar power would appear to have taken off in both the Andaman & Nicobar Island (solar power generation 35 GWh) and Karnataka (solar power generation 12332 GWh), contributing >20% of their respective total power generation. This would not allow for an analysis of the solar power S-curves for individual states that adequately answers my research questions.

Once the 'beginning of the movement' has been defined, it is possible to divert attention to its 'rate'.

"G" – the rate

As discussed in Chapter 2, there are several ways to measure growth in the technology diffusion literature, with the duration of transition (Δt) being the most popular metric. This thesis draws from the work of Cherp *et al.* (forthcoming) and uses their newly proposed growth metric, "G", to measure the growth rates of solar deployment in Indian states. G corresponds to the maximum slope of the S-curve and measures the maximum growth rate of technology adoption using growth parameters that can be easily estimated from it. Cherp *et al.* (forthcoming) developed this new metric with the aim of assessing the feasibility for the growth of renewable energy technologies to match the levels required to meet the climate targets. Citing a number of computational tests and experiments, they argue that G is "more robust than other aggregate growth metrics" such as Δt. This thesis adopts G for reasons outlined below.

Since it is expressed in units of either capacity or generation growth it has a distinct physical meaning. Moreover, it can also be easily normalized to the total electricity supply. This characteristic allows for easy comparison between systems, and also between historical growth rates and the rates required to meet future targets. Moreover, the metric also corresponds to the actual dynamics of the technology adoption cycle with the inflection point of the S-curve representing a stage where opposing forces act to expand and restrain the growth of the technology counterbalance. Consequently, it is better suited to the analysis of policy compared to metrics such as Δt or compound annual growth rates. This thesis measures growth rates of solar power generation (GWh/year), capacity installation (MW/year) as well as the share of solar power in the electricity supply during the year of maximum growth.

Another advantage of G is that it reflects several properties of the technology's diffusion trajectory in a given context, and is isolated from fluctuations due to year-on-year changes or technology lifecycle phases. Moreover, it also allows for a direct investigation of the relationship between the spatial (core vs periphery), temporal (early vs late) characteristics of technology adoption with the market penetration by enabling a comparison of Δt with the S-curve asymptote (or saturation value "L"). It thereby facilitates a new way to measure and compare the speed of transition between different systems (different Indian states in the case of this thesis). These estimates of G can be easily validated against empirically observed maximum growth rates.

In addition to G, this thesis also defines and analyzes the following growth parameters:

> **The 'curve maturity'** – the ratio of the latest point on the curve which corresponds to the last empirical datapoint, to the value of the curve asymptote. A higher curve maturity implies a more advanced position on the technology lifecycle, and closer proximity to the saturation phase.
>
> **The transition duration** – the time taken for the technology to grow from 10% to 90% of the asymptote (L).

This curve maturity and recent, empirical growth rates were used to further categorize the growth phase into the accelerating, stable, and stalling growth phases (described in Section 3.2).

The growth of both capacity installation and power generation was analyzed. Much of the research on solar PV in India, and the government's targets themselves, view the technology's growth exclusively through the lens of installed capacity; they rarely highlight how this capacity translates into actual power generation. An emphasis on generation is important given that the rate and extent of decarbonisation in the power sector depend on increasing the relative share of low-carbon sources in the total power supply rather than adding capacity alone.

3.1.3. The factors affecting the deployment of solar power

In order to analyze the factors influencing the takeoff of solar power in different Indian states, this thesis draws on insights from the literature review to design and subsequently test a set of deductive hypotheses. These hypotheses are constructed on the basis of explanatory variables that previous studies have identified as influencing the deployment of solar power. The hypotheses and their respective explanatory variables are listed as follows:

> **H1**: Solar was deployed to a greater degree in states with greater economic affluence as they were better positioned to invest in a new, and relatively expensive technology. The per capita state gross domestic product (GDP) at constant prices from 2013 was used as a proxy for state affluence.
>
> **H2**: States with larger electricity systems deployed solar more extensively because of their larger absolute power demand. The total annual state electricity generation for 2013 was used as a proxy for system size.
>
> **H3**: States experiencing a greater surge in power demand were likelier to have deployed solar as a means to plug the gap. The percentage change in state power demand over 5 years (2014-2019) was used as a measure of change in power demand.

H4: States with a greater power supply deficit were likelier to have deployed more solar power to bridge the gap. The power supply deficit was operationalized using annual state-wise energy balances from Busby and Shidore (2021).

H5: States with a greater average Global Horizontal Irradiance (GHI) deployed more solar as they receive greater solar radiation per unit area on a daily scale.

H6: States with a greater overall potential to generate power from solar energy deployed more solar. Solar power generation potential calculated by Deshmukh *et al.* (2017) incorporating land availability and site suitability criteria for different states was used.

H7: States that incurred greater coal transportation costs deployed more solar as an economical alternative to thermal power. Coal transportation costs collated by Busby and Shidore (2021) were used.

H8: States with more functional DISCOMs were better able to integrate solar power into their distribution grids and consequently deployed more solar. Average DISCOM rating scores calculated by Busby and Shidore (2021) were used.

H9: States with a more favorable business environment attracted greater private investment into solar deployment. The Indian government's Ease of Doing Business scores from 2015 were used to quantitatively compare the business-friendliness of states.

H10: Higher solar power purchase tariffs attracted more players into the solar power sector and contributed to greater solar deployment.

3.1.4. Feasibility

This thesis follows Wilson *et al.* (2013), Jewell and Cherp (2020) and defines feasibility on the basis of historical growth rates. Its focus is on assessing the feasibility of India and its states achieving their respective solar capacity installation targets under the JN-NSM and other policies. It takes inspiration from Wilson *et al.* (2013) who compare historical growth rates achieved in other (almost exclusively OECD/industrialized) countries to the rates required to achieve climate targets but does not replicate them. Instead, I use historical rates that have been empirically observed in the same system (India or individual states), and compare these to the rates required to meet respective solar deployment targets. Thus, I do not assess feasibility based on what has been achieved by other (very different) countries in their own contexts, but on what these systems have experienced themselves. I argue that this method better reconciles the socio-economic and political heterogeneities within India, and paints a more reliable picture of the future of technological growth in the specific contexts of different Indian states.

3.2. Method

This section outlines the methodology that this thesis uses to answer the research questions stated in Chapter 1. First, it describes the criteria used to select states and UTs for analysis given considerations for solar deployment, data availability, and system size. Second, it defines and operationalizes technology 'takeoff' to classify states and UTs and further outlines a series of hypotheses to investigate which factors influence it. Third, it discusses the measurement of growth trajectories and parameters for solar PV at the national and state levels. The criteria used to classify states and UTs on the basis of growth phases is described and a method to study the impact of early/late adoption on growth rates is also highlighted. Fourth, it illustrates how the national and state JN-NSM targets were quantitatively analyzed to assess their feasibility. Finally, the data sources used in the analyses are listed.

3.2.1. Sample selection

India is composed of 28 states and eight UTs. 16 of these units with annual electricity generation <10 TWh were excluded from the analysis sample. Given the susceptibility of small-sized systems to short, one-off bursts of fast growth followed by stagnation, their analysis may produce misleading growth rates that skew the final results. Many of these states lacked significant utility-scale solar PV deployment (annual solar power generation < 50 GWh). By virtue of their small system sizes, no UTs qualified for the final analysis sample. From the remaining 20 units, another 3 were dropped from the analysis sample as they generated <50 GWh of solar power annually.

Thus, the final sample included 17 states which cumulatively accounted for 99% of the total national installed solar power capacity and 70% of the total national power generation in 2021.

Table 3 lists the states, UTs, and their respective categories post-selection.

Table 3. Classification of states by sampling criteria

Category	States/UTs	Number
Analyzed	Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamil Nadu, Telangana, Uttarakhand, Uttar Pradesh, West Bengal	17
Excluded: Minimal/no utility-scale solar PV deployment (< 50 GWh annual solar power generation)	Jammu & Kashmir, Himachal Pradesh, Sikkim	3
Excluded: Annual electricity generation <10 TWh	Andaman & Nicobar Islands, Assam, Arunachal Pradesh, Chandigarh, Dadar & Nagar Haveli and Daman & Diu, Delhi, Goa, Kerala, Ladakh, Lakshadweep, Manipur, Meghalaya, Mizoram, Nagaland, Puducherry, Tripura	16

Note: The analysis in this thesis also excludes the utility-scale solar PV installed in various National Thermal Power Corporation (NTPC) plants across the country.

3.2.2. Measuring solar takeoff

Classifying states on the basis of solar power 'takeoff'

Solar power is defined to have achieved "takeoff" in a particular state if the total annual power generated from the source exceeded 500 GWh in any year. This definition of takeoff was used to classify states as either having achieved 'takeoff' or being 'pre-takeoff'.

Additionally, for a particular state, the first year in which solar power crossed the takeoff threshold was defined to be its ‘takeoff year’. The takeoff year was used to sequence the states in chronological order of takeoff, and qualitatively assign them early/late adopter status.

Analyzing the drivers of takeoff

This thesis tests a set of ten hypotheses to analyze the factors influencing the takeoff of solar power in different states. The hypotheses and their respective explanatory variables are summarized in Table 4. Hypothesis and associated explanatory variables for the analysis of takeoff.

Table 4. Hypothesis and associated explanatory variables for the analysis of takeoff

	Hypothesis	**Variable**
Solar achieves takeoff in states where there is...	greater economic affluence	Per Capita State Gross Domestic Product at constant prices (INR), 2013
	a larger system size	Total electricity supply (GWh), 2013
	a higher increase in power demand	Change in power demand over last 5 years w.r.t base year (% GWh), 2014-2019
	a greater power supply deficit	Average energy balance (power supply deficit)
	greater average GHI	Average Global Horizontal Irradiance (KWh/m2/day)
	greater solar power generation potential	Solar power generation potential (TWh)
	a higher coal transportation cost	Coal transportation cost (INR/kWh)
	a better functioning DISCOMs	Average DISCOM rating score (Busby and Shidore 2021)
	a more favorable business environment	Ease of Doing Business score, 2015
	a higher solar power purchase tariff	Initial solar power tariff (INR/kWh)

Pearson’s product-moment correlation coefficients for variable pairs with takeoff as the dependent variable coded as 1 (yes) and 0 (no), and the set of independent variables listed in Table 4 were calculated. The significance of the correlation was tested using a one-tailed t-test with α=0.05. By virtue of the correlation statistic, these results were not intended to prove a causal relationship between the variables, but to simply test the outlined hypotheses.

I recognize a logistical regression is better suited to a cause-effect analysis involving binary variables, but the sample was not large enough for the method to be used reliably.

For the sample of states that had achieved takeoff, a set of pair-wise linear regressions with the takeoff year as the dependent variable, and the same set of independent variables in Table 4 were performed. This was done to investigate the relationship between these factors and the chronological sequence of takeoff. An ANOVA test was performed to test the statistical significance of the relationships. A Pearson's product-moment correlation analysis was also performed simultaneously.

3.2.3. Measuring the growth of solar power

Once the states where solar power had achieved takeoff were identified, the next step was to quantify how fast the technology was being deployed. Three statistical growth models were fit to empirical solar power generation data from 2013-2021 for individual states, and growth parameters were derived from the trajectories thus generated.

Fitting growth models and calculating G

This thesis uses G, the maximum annual growth rate metric developed by Cherp *et al.* (forthcoming), to quantify the increase in the deployment of solar power in various Indian states. The two primary growth models included a symmetric logistic model where growth slows down after the inflection point (t_0), and an asymmetric Gompertz model where growth extends for a longer duration post-inflection. They are mathematically represented as:

$$\text{Logistic model } f(t) = \frac{L}{1 + e^{-k(t-t_0)}}$$

$$\text{Gompertz model } f(t) = Le^{-e^{k(t-t_0)}}$$

Code developed by Cherp *et al.* (forthcoming) was leveraged to perform a least-square curve fitting for the three models using the Gauss-Newton and Levenberg-Marquardt algorithms in the R programming environment. It calculated the maximum growth rate G at t_0 (the maximum slope of the curves). Additionally, G was normalized to the total power supply for that year in order to facilitate comparisons between systems of differing sizes. In both the logistic and Gompertz models, growth accelerates until the inflection point, where it is almost linear, and then slows down as it reaches the curve asymptote (L) which represents the saturation-level for the technology. In case of the logistic curve, the inflection point (and consequently G), is located at 50% of L, while for the Gompertz curve, it is located at 37% of L; the values of L and k (growth constant) for each fit were subsequently used to calculate G for each model.

Maximum growth rate G, logistic $G_{\log} = \frac{Lk}{4}$

Maximum growth rate G, Gompertz $G_{gomp} = \frac{Lk}{e}$

Additionally, the transition duration (ΔT) and the curve maturity were computed.

Transition duration, logistic $\Delta t_{\log} = \frac{\ln(81)}{k}$

Transition duration, Gompertz $\Delta t_{gomp} = \frac{\ln\left(\frac{\ln(0.1)}{\ln(0.9)}\right)}{k}$

In addition to the logistic and Gompertz model, a log-linear model was also fit to the data. Unlike the former two, this model is not S-shaped and may be better suited to erratic systems in early stages of growth. It follows the logistic curve until t_0, after which it grows linearly at a constant rate equal to G.

G was calculated for all states with logistic curve maturity >50%. For statistical analysis of G, all cases with 100% maturity and a transition duration <2 years were further excluded to control for short, one-off growth bursts followed by stagnation as they do not indicate sustained growth rates.

Average annual growth rates for the latest three years, and five-year moving averages were also calculated for the states in the final sample. The quality of the model fits was compared by calculating the residual sum of squares (RSS) for each case.

Sensitivity analysis

A sensitivity analysis for the growth parameters was conducted by removing the last data point for 2021. The model fitting and growth parameter estimations were performed again with the reduced dataset up to 2020. The values for different growth parameters including G for the two sets of data from all three growth models were compared and the variation between them was measured. This quantitative variation was used as a measure of robustness for the values of G in particular, and the methodology in general.

Categorizing growth phases

Following the generation of model fits and computation of the respective growth parameters, the states were classified as having 'accelerating', 'stalling', or 'stable' growth using the criteria developed by Cherp *et al.* (forthcoming). These criteria are listed in Table 5.

Table 5. Growth phases categories with their respective criteria.

Category	Criteria
Accelerating growth	The inflection point is located in the future in both models. The maturity of the logistic curve is <50% and the estimates for G usually diverge between the two models. Such uncertain estimates for G are not included in descriptive statics or regression analysis.
Stalling growth	Both the logistic and Gompertz curve maturities are >90%, and the 3-year average of the most recently measured empirical growth is less than 60% of the estimated G.
Stable growth	All states/UTs that are neither 'accelerating' nor 'stalling'. Their maturities are usually in the 50-90% range

The growth trajectories and parameters of individual states in each category were further detailed, analyzed, and compared. Median values of the various model parameters for each state were calculated and compared against the median values for each category. The states undergoing 'accelerating' growth were excluded from statistical analyses and comparisons by virtue of their low curve maturities, and unstable parameters.

Measuring the effect of takeoff year on growth rates and regression analysis of growth rates

The effect of the takeoff year on the maximum annual growth rate G and on the transition duration ΔT for both the logistic and Gompertz models was directly tested by performing a univariate linear regression analysis. Pair-wise linear regressions of the maximum growth rate and transition duration with the same set of independent variables listed in Table 4 were also performed individually to identify the influence of factors other than early/late adoption. This analysis was replicated for both the logistic and Gompertz model outputs, and ANOVA tests were performed to evaluate the statistical significance of relationships.

3.2.4. Assessing the feasibility of targets

National targets

2022 JN-NSM target

Capacity

The national capacity target for 2022 was analyzed using timeseries data for total installed solar capacity from 2010-2021. The annual additions in capacity and the average growth rate over the last three years (2019-2021) were calculated. The data was fit to logistic, Gompertz, and log-linear growth models and their respective growth parameters were estimated. The feasibility of achieving the target was assessed by comparing the deficit between the actual installed capacity as of March 2021 and the 2022 target against the maximum growth rates estimated by different models, as well as the empirical three-year average growth rate.

Generation

A generation-centric analysis was performed using the same method, where the capacity targets were translated into estimated generation targets. A capacity utilization factor (CUF) of 18% was used for this calculation. Generation data from three independent datasets – IndiaStat-CEA, IEA Energy Balance, and estimates from the actual installed capacity – were each used to separately calculate three-year average growth rates for the latest data, as well as the deficits between actual generation and the estimated yearly targets. All three data were separately fit to logistic, Gompertz, and log-linear growth models and respective G values were estimated. The feasibility of achieving the target in the case of each data was assessed by comparing the respective generation deficits against values for G from the three models and the three-year average growth rates.

2027 and 2030 capacity targets

The 2027 and 2030 'soft' targets were appended to the existing timeseries data up to 2021, and the 2022 target roadmap as additional datapoints. The average annual capacity additions required to meet the 2027 and 2030 targets were calculated by dividing the net additions for each target by their respective timeframes (e.g. the 2027 target involved installing 100 GW of capacity in 5 years, yielding an average annual addition of 20 GW per year). These average annual additions were used to create a roadmap for the targets.

This new data was fit to logistic, Gompertz, and log-linear models and their respective growth parameters were calculated to determine the growth rates required to fulfil the targets. The outputs from the growth models and the average growth rates from the abovementioned roadmap were compared to the empirical growth rates measured in the previous section and the gap between them was quantified in order to evaluate the feasibility of meeting the targets.

State-level targets

Capacity

In case of the state-level targets, extended timeseries data for the installed solar capacity was not available. Moreover, unlike the case of the national target, there was no breakdown of the final targets into yearly increments, and no distinction was made between the total and ground-mounted targets. Thus, the analysis was fairly simplistic. For each state, the total installed solar capacity as of 2021 was directly compared to the 2022 targets to calculate the deficit. The average annual capacity addition over the latest 3 years (2019-21) was calculated for each state and compared to the respective deficit to evaluate if the growth rate was sufficient to fulfil the target.

Generation

Like in the national case, the capacity targets were translated into state-wise generation targets assuming a CUF of 18%. The gap in actual generation in 2021 and the estimated 2022 target was calculated for each state. The calculated gaps for each state were compared with previously calculated values of G for different models and the three-year average growth rates to assess feasibility. Additionally, the asymptote of the model trajectories was also compared to the targets to see if they were compatible.

3.2.5 Data Sources

The analysis in this thesis uses a novel dataset that was compiled using the following data:

- State-wise annual, utility-scale solar power generation (2013-2021) from IndiaStat (2021), CEA and CEEW (2021)
- National annual, utility-scale solar power generation (2013-2021) from IndiaStat (2021), CEA and CEEW (2021), IEA (2020b)
- State-wise total installed grid-connected solar power generation capacity (2019-2021) from CEA and CEEW (2021)
- National total installed grid-connected solar power generation capacity (2013-2021) from IndiaStat (2021), CEA and CEEW (2021)
- State-wise total annual electricity supply (2013-2021) from IndiaStat (2021b) and National Power Portal (2021)
- National total annual electricity supply (2013-2021) from IEA (2020b) and National Power Portal (2021)

The data used in the regression and correlation analyses comes from Busby and Shidore (2021), Deshmukh *et al.* (2017), Bhowmik (2020), Reserve Bank of India (2021) and from my own calculations from the data mentioned above. Relevant data tables can be found in the Appendix.

Chapter 4: Results and analysis

4.1. Measuring solar takeoff

4.1.1. Takeoff – where and when?

The takeoff threshold of 500 GWh/year of solar power generation described in Chapter 3 was used to classify the states in the final analysis sample as shown in Table 6.

Table 6. Takeoff years for Indian states.

State	Takeoff Year
Gujarat	2013
Rajasthan	2014
Madhya Pradesh	2015
Maharashtra	2016
Tamil Nadu	2016
Andhra Pradesh	2017
Karnataka	2017
Punjab	2017
Telangana	2017
Uttar Pradesh	2018
Chhattisgarh	2021
Bihar	Pre-takeoff
Haryana	Pre-takeoff
Jharkhand	Pre-takeoff
Odisha	Pre-takeoff
Uttarakhand	Pre-takeoff
West Bengal	Pre-takeoff

As of March 2021, solar power has taken off in 11 of the 17 states that were part of the final analysis sample. Starting in the western region, solar power generation first crossed the 500 GWh threshold in Gujarat in 2013, followed by Rajasthan in 2014. Solar power achieved takeoff in Madhya Pradesh in 2015, followed by Maharashtra and Tamil Nadu in 2016. 2017 was a particularly active year with four states – Andhra Pradesh, Karnataka, Punjab, and Telangana – crossing the threshold. The incidence of takeoff appeared to have slowed after 2018, with no states taking off in 2019 and 2020. Chhattisgarh became the latest state to have achieved takeoff in 2021. Spatially, there are no states from the eastern region in the takeoff sample, and with the exception of Haryana and Uttarakhand, all other states in the pre-takeoff category come from this region. The group of 'takeoff' states together accounted for 56% of the country's total power generation in 2021.

As of March 2021, 6 states – Bihar, Haryana, Jharkhand, Odisha, Uttarakhand, and West Bengal – from the final analysis sample had not achieved takeoff. These states cumulatively accounted for 14% of India's total power generation in 2021.

4.1.2. Which factors affected the presence and the timing of take-off?

In order to better understand which factors may be linked to the incidence of takeoff in Indian states, Pearson's product-moment correlation analyses were performed for various variable pairs. The Pearson's r coefficients and p-values for each pair is listed in Table 7.

Table 7. Correlation analysis of factors influencing takeoff.

Variable	Takeoff [1 = Yes, 0 = No]	
	Pearson's r	**p-value**
Per capita state GDP	0.16	0.27
Total electricity supply	-0.06	0.41
Change in power demand	0.02	0.47
Average energy balance	-0.12	0.32
Average GHI	0.68	**0.01**
Solar power generation potential	0.38	0.07
Coal transportation costs	0.45	**0.04**
Average DISCOM rating	0.10	0.36
Ease of Doing Business score	0.47	**0.03**
Solar power purchase tariffs	0.04	0.44

There are significant positive correlations between the incidence of takeoff and three variables viz. the Ease of Doing Business score, the average Global Horizontal Index (GHI), and coal transportation costs. These findings confirm hypotheses H5, H7, and H9 listed in Chapter 3. Thus, the incidence of takeoff was linked to more (i) favorable business environments, (ii) plentiful solar energy resources, and (iii) expensive thermal power.

4.1.3 Takeoff Year – What explains the inter-state sequence?

The same independent variables were also used to run pair-wise linear regressions with the takeoff year to investigate which factors influence the takeoff timing (Table 8). The Pearson's product-moment correlation coefficients and associated significance levels were also computed.

Table 8. Correlation and linear regression analyses of takeoff with independent variables.

Independent Variable	Takeoff year			
	Pearson's r	p-value	R^2	p-value
Per capita state GDP	-0.37	0.13	0.136	0.26
Change in power demand	-0.11	0.37	0.013	0.74
Total electricity supply	-0.08	0.40	0.140	0.23
Ease of Doing Business score	-0.26	0.22	0.069	0.44
Solar power generation potential	-0.63	**0.03**	0.394	**0.05**
Average GHI	-0.37	0.13	0.135	0.27
Coal transportation costs	-0.37	0.13	0.138	0.26
Average DISCOM rating	-0.27	0.21	0.072	0.43
Average energy balance	-0.35	0.14	0.125	0.28
Solar power purchase tariffs	0.52	0.053	0.265	0.10

The only significant relationship observed was with states' total solar power generation potential – states that had a higher overall generation potential after accounting for land availability and site suitability were found to achieve solar takeoff earlier.

4.2. Measuring post-takeoff growth

Post-takeoff, the growth of solar power has been found to generally follow a S-shaped curve. To analyze the growth of solar power in states that had achieved takeoff, empirical time series data for solar power generation were fit to the logistic, Gompertz, and log-linear growth models and their respective growth parameters were estimated.

Out of the 11 states that had achieved takeoff, growth was found to be accelerating in three states viz. Chhattisgarh, Gujarat, and Rajasthan. In these states, both the logistic and Gompertz projected the maximum growth year i.e., the inflection point of the growth curve to be in the future. Among the remaining states, four states viz. Andhra Pradesh, Punjab, Telangana, and Karnataka fell into the ‘stalling’ growth phase, where the curve maturity (i.e., the ratio of solar power generation in 2021 to the asymptote of the growth curve) exceeded 90% and the average growth over the last three years slowed to below 60% of the maximum rate G. Lastly, the states of Madhya Pradesh, Maharashtra, Tamil Nadu, and Uttar Pradesh fit neither of the two categories and were classified as undergoing ‘stable’ growth.

4.2.1. Accelerating growth phase

The three states in the accelerating growth phase include Chhattisgarh, Gujarat, and Rajasthan. The growth parameters for the logistic, Gompertz, and log-logistic growth models for these states are listed in Table 9. The growth of solar power in these states is characterized by low logistic curve maturity, long transition durations, and very high growth rates. Figure 3 illustrates the growth curves for each of the three states.

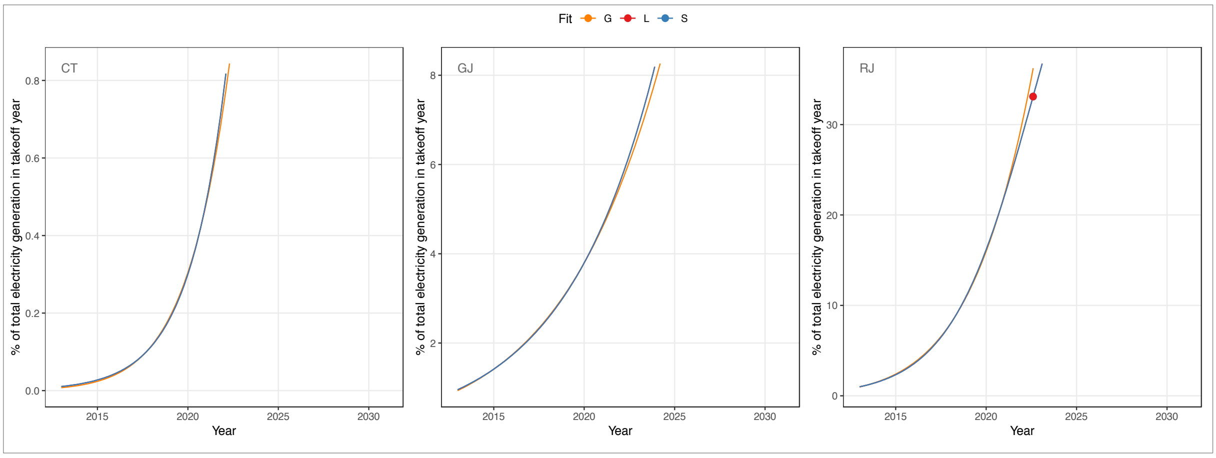

Figure 3. Growth model fits for states in the accelerating growth phase.
(G = Gompertz, L = Log-linear, S = Logistic)

Among the three states, Rajasthan has a relatively higher logistic curve maturity of 33.34%. Consequently, its values for ΔT and G from the logistic and log-linear models are more comparable to estimates for other states in the takeoff sample. Both the logistic and Gompertz models estimated its inflection point to be between 2022-2023 with a maximum annual growth rate of 3303 GWh, or 6.11% per year (when normalized to the state’s total power generation). This was significantly higher than both, its average growth rates for the last three years (2019-21) and its maximum five-year moving average growth between 2013-2021.

In comparison, Gujarat has a much lower logistic curve maturity of 0.18%. This corresponded with extremely high values for G (all larger than its total power generation in 2021) and significantly longer transition durations across each of the three models. The inflection points were also set further – at least 3 decades – into the future.

Chhattisgarh was similar to Gujarat in that its logistic curve maturity was also very low (0.41%). However, like Rajasthan, its parameters from the logistic and log-linear models were more modest, with the point of inflection occurring between 2032-2033 and G equal to 14.09%. It is important to note that the state only recently achieved takeoff in 2021, and had zero datapoints post-takeoff; it is possible that the addition of future datapoints may significantly change its parameters, and consequently affect its classification.

Table 9. Growth parameters for accelerating states.

State	Takeoff year	Fit	T_{max}	Logistic Curve Maturity	G%	G (GWh)	ΔT	Avg. Growth (2019-2021)	Max. observed 5-year moving average
		S	2032.5		14.1%	19045	9.2		
CT	2021	G	2083.9	0.41%	624.4%	844139	79.7	0.15%	0.11%
		L	2032.5		14.1%	19045			
		S	2053.0		110.6%	114942	22.3		
GJ	2013	G	2208.7	0.18%	15483.3%	16092082	222.2	0.79%	0.58%
		L	2053.1		113.3%	117748	23.0		
		S	2022.6		6.1%	3303	10.1		
RJ	2014	G	2060.3	33.34%	252.5%	136500	64.1	3.62%	2.83%
		L	2022.6		6.1%	3303			

4.2.2. Stalling growth phase

Four states from the sample of 11 'takeoff' states were classified as having 'stalling' growth. These include Andhra Pradesh, Punjab, Telangana, and Karnataka. All four of these states achieved takeoff in 2017, and are characterized by high curve maturities, slowing recent growth rates, and converging G and ΔT values (Table 10). They all had larger median G% values (3.24% vs 1.47%) and shorter median transition durations (2.78 years vs 4.12 years) compared to the medians for the sample of non-accelerating states. This group's median G% (3.24% vs 0.53%) and ΔT (2.78 years vs 5.27%) were also respectively higher and shorter than the medians for the 'stable' states.

Figure 4 illustrates the growth model fits for the stalling states.

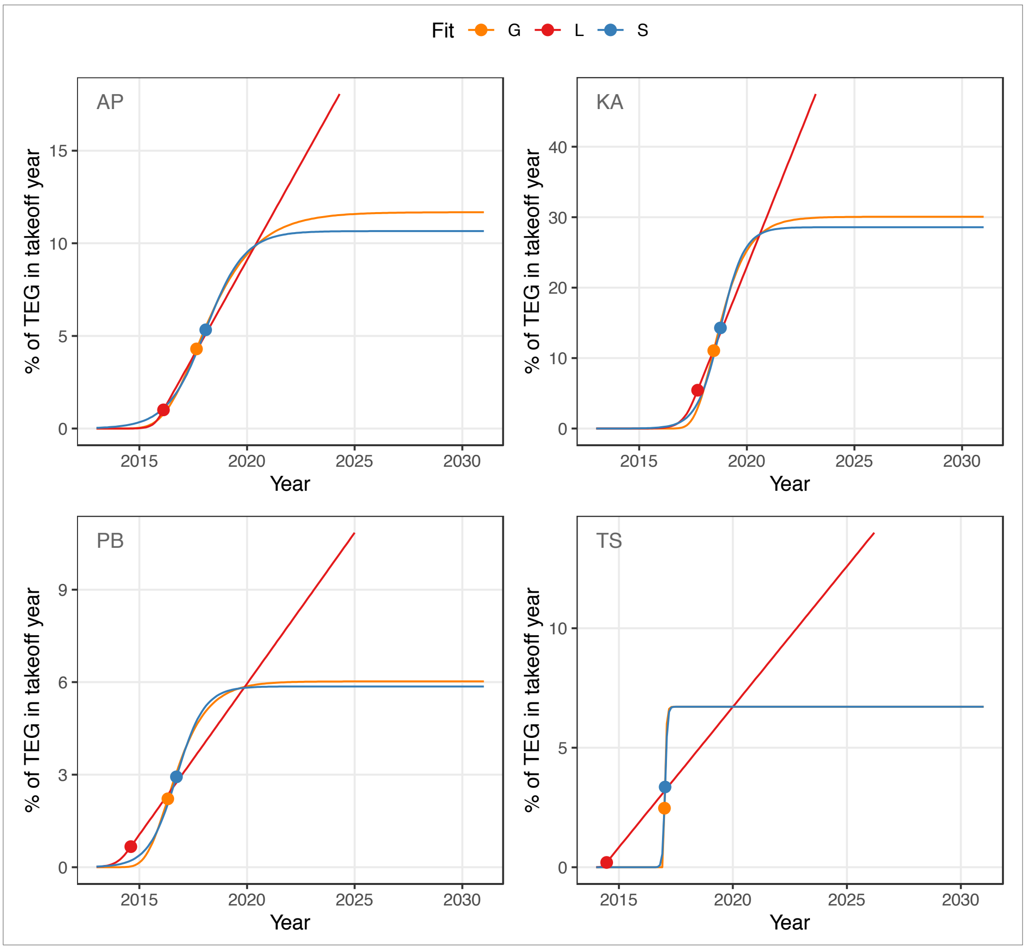

Figure 4. Growth model fits for states in the stalling growth phase.
(G = Gompertz, L = Log-linear, S = Logistic)

In case of Andhra Pradesh, the maturity of the logistic curve was 96.15% while that for the Gompertz curve fell slightly short of 90% at 89.18%. However, both the absolute and percentage values for the average growth rate over 2019-2021 were found to be below 60% of the corresponding G values for the logistic and Gompertz models. Thus, the state was classified as being in the 'stalling' growth phase. The absolute and percentage values of G for both the logistic and Gompertz models converged within a 5% difference, while the ΔT values converged to within 20% of each other. G% ranged between 2.33-2.79%.

Both the logistic and Gompertz models had maturities >99% for Punjab, with both the absolute and percentage values of average growth between 2019-2021 falling below 60% of the corresponding G values for all three models. The absolute and percentage values of G for the logistic and Gompertz models converged to within 3% and 10% respectively, and the ΔT values converged to within 20% of each other. G% was found to range from 1.27-2.49%, which were the lowest rates in this group.

Telangana had logistic and Gompertz curve maturities >99%, and average percentage growth for 2019-2021 lower than the corresponding G values for all three models. The absolute value of the three-year average growth was below the G values for both the logistic and Gompertz models. The absolute and percentage values of G for the logistic and Gompertz models converged to within 2% and 15% of each other respectively, and ΔT was found to vary by 3%. The values of G% varied from 3.69-7.36%.

The logistic and Gompertz curve maturities for Karnataka were >94%, but it's compatibility with the second 'stalling' criteria was not as clear-cut. The absolute value of the average growth rate between 2019-2021 was lower than 60% of the corresponding G for the logistic model but not for the Gompertz and log-logistic models, while the percentage value was lower than 60% of the corresponding G value for the Gompertz model but not for the other two models. The absolute and percentage values of G for the logistic and Gompertz models converged to within 3% and 8% of each other respectively, and ΔT was found to converge within 12%. Considering the shape of the growth trajectories (Figure 4), the calculated parameters, and the converging G and ΔT values, it was tentatively classified as having 'stalling' growth. Karnataka is also an outlier in that it had significantly higher G% values (7.50-12.30%) as opposed to other (non-accelerating) states in the sample.

Table 10. Growth parameters for stalling states.

State	Takeoff year	Fit	Tmax	Maturity	G%	G (GWh)	ΔT	Avg. % Growth (2019-2021)	Avg. Growth (2019-2021)	0.6 G%	0.6 G	Max. observed 5-year moving average
AP	2017	S	2018.1	96.15%	2.79%	1919	3.98	1.51%	975	1.68%	1151	1.99%
		G	2017.7	89.18%	2.65%	1818	4.76			1.59%	1091	
		L	2016.1	N/A	2.33%	1360	N/A			1.40%	816	
PB	2017	S	2016.8	99.87%	2.26%	599	2.85	0.36%	90	1.36%	359	1.22%
		G	2016.4	99.03%	2.49%	580	3.12			1.49%	348	
		L	2015.2	N/A	1.27%	259	N/A			0.76%	155	
TS	2017	S	2017.7	99.81%	6.42%	3131	2.30	1.70%	832	3.85%	1879	2.90%
		G	2017.4	99.11%	7.36%	3194	2.36			4.42%	1916	
		L	2016.1	N/A	3.69%	1359	N/A			2.21%	815	
KA	2017	S	2018.8	98.28%	11.42%	5684	2.42	7.13%	3313	6.85%	3411	5.27%
		G	2018.5	94.54%	12.30%	5493	2.72			7.38%	3296	
		L	2017.7	N/A	7.50%	3352	N/A			4.50%	2011	

4.2.3. Stable growth phase

The four remaining states – Madhya Pradesh, Maharashtra, Tamil Nadu, and Uttar Pradesh – were classified as being in the 'stable' growth phase. They were characterised by curve maturities that fell between those of the 'accelerating' and 'stalling' states. The average absolute and percentage values of growth observed between 2019-2021 for these states were above 60% of the corresponding G and G% values estimated by the three models. The median G% values for this group of states was lower than those for both the non-accelerating sample (0.53% vs 1.47%) and the 'stalling' group of states (0.53% vs 3.24%). This group also had a longer median transition duration of 5.27 years compared to the non-accelerating sample (4.12 years) and the 'stalling' group (2.78 years). The growth parameters for each of the states in this category are listed in Table 11, and their growth curves are illustrated in Figure 5.

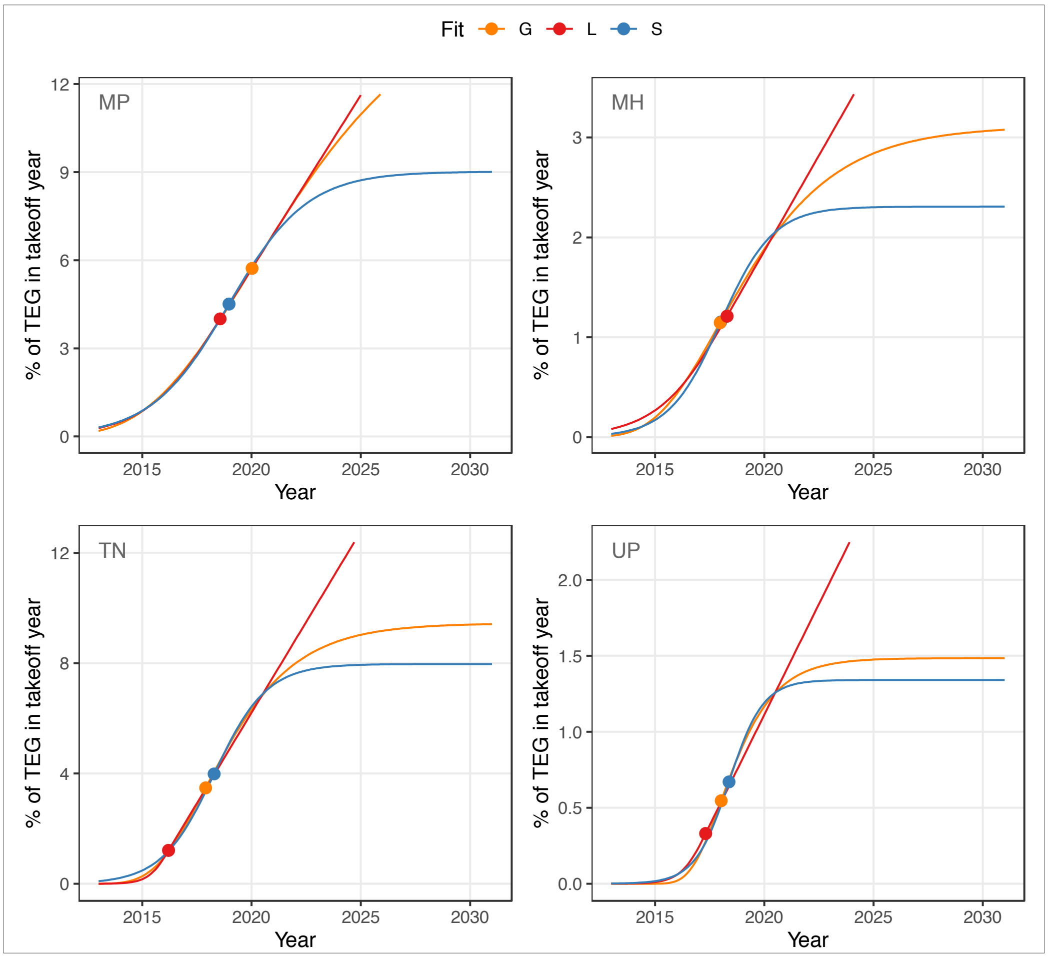

Figure 5. Growth model fits for states in the stable growth phase.
(G = Gompertz, L = Log-linear, S = Logistic)

In case of Madhya Pradesh, the logistic and Gompertz curve maturities were 75.86% and 44.47% respectively. The absolute and percentage values of the average growth between 2019-2021 for all three models were higher than their 60% of their respective G and G% values. The values of G and G% for the logistic and Gompertz models respectively converged to 5% and 4% of each other, and ΔT differed by 14%. G% ranged from 0.60%-0.65%.

Maharashtra had a logistic curve maturity >90% which is characteristic of 'stalling' states, but its Gompertz curve maturity was much lower at 69.86%. Moreover, its absolute and percentage values for the average growth rates between 2019-2021 were greater than the corresponding 0.6 G and 0.6 G% values for all three models. As a result, it was classified as 'stable'. Both G and G% for the logistic and Gompertz models converged within 19% of each other, while ΔT varied by 73%. Its values for G% were in the 0.36%-0.46% range, and it had the lowest median G% value in this group.

Tamil Nadu was similar to Maharashtra, with the logistic and Gompertz curve maturities >90% and <90% respectively. It too had average growth rate values greater than the corresponding 0.6 G and 0.6 G% values for all three models. Its G and G% values for the logistic and Gompertz models converged to within 9% of each other while ΔT varied by 34%. G% was found to range from 1.32%-1.54%.

Uttar Pradesh also had a logistic curve maturity >90%, but its Gompertz curve maturity was 88.97%, which was marginally lower than the 90% threshold for 'stalling' states but significantly higher than the other 'stable' states. However, since its average growth rate values were also marginally higher than the corresponding 0.6 G% and 0.6 G values for all three models, it was classified as 'stable'. Its G and G% values for the logistic and Gompertz models both converged to within 8% of each other. ΔT varied by 25%, and G% ranged from 0.31% to 0.43%.

Table 11. Growth parameters for stable states.

State	Takeoff year	Fit	Tmax	Maturity	G%	G (GWh)	ΔT	Avg. % Growth (2019-2021)	Avg. Growth (2019-2021)	0.6 G%	0.6 G	Max. observed 5-year moving average
		S	2019.0	75.86%	0.65%	787	7.82			0.39%	472	
MP	2015	G	2020.0	44.47%	0.62%	751	14.55	0.54%	634	0.37%	451	0.55%
		L	2018.6	N/A	0.60%	736	N/A			0.36%	441	
		S	2018.0	92.41%	0.46%	566	5.26			0.27%	339	
MH	2016	G	2018.0	69.86%	0.37%	456	9.08	0.33%	410	0.22%	274	0.34%
		L	2018.3	N/A	0.36%	448	N/A			0.22%	269	
		S	2018.3	90.53%	1.54%	1268	5.28			0.92%	761	
TN	2016	G	2017.9	77.18%	1.40%	1157	7.08	1.08%	899	0.84%	694	1.25%
		L	2016.2	N/A	1.32%	1005	N/A			0.79%	603	
		S	2018.4	96.67%	0.43%	554	3.41			0.26%	332	
UP	2018	G	2018.0	88.97%	0.39%	507	4.27	0.27%	343	0.24%	304	0.26%
		L	2017.3	N/A	0.31%	374	N/A			0.19%	224	

4.2.4. India's sub-national solar landscape

Table 12 summarizes the growth parameters of all states in the analysis sample and lists information about the other Indian states and UTs, and Figure 6 illustrates the state-wise solar power generation in different Indian states and UTs during 2021.

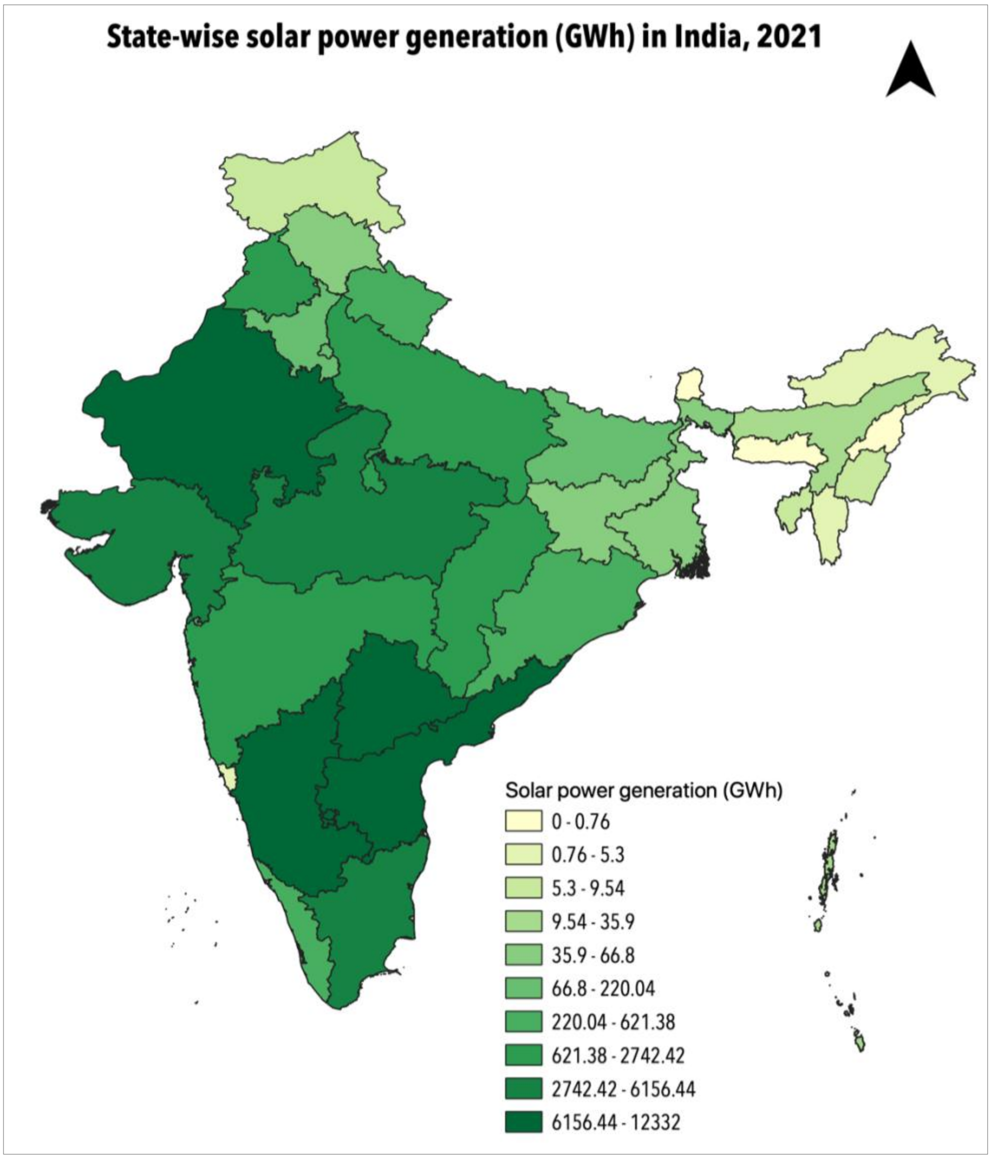

Figure 6. State-wise solar power generation (GWh) in India, April 2020 to March 2021.

Table 12. Solar power in Indian states and UTs.

State/UT	Region	TES (TWh)	Solar gen. in 2021 (GWh)	Takeoff Year	Category	G (best-fit, GWh)	G% (best-fit)
Chhattisgarh	West	135.2	669.5	2021	Accelerating		
Madhya Pradesh	West	129.5	4383.3	2015	Stable	751.3	0.62%
Uttar Pradesh	North	127	1707.9	2018	Stable	554	0.43%
Maharashtra	West	117.6	2332.2	2016	Stable	565.6	0.46%
Gujarat	West	107	4419.7	2014	Accelerating		
West Bengal	East	76	66.8	Pre-takeoff	N/A		
Tamil Nadu	South	70.1	5602.4	2016	Stable	1004.9	1.32%
Odisha	East	62.1	428.9	Pre-takeoff	N/A		
Rajasthan	North	54.1	9975.9	2015	Accelerating		
Andhra Pradesh	South	52.7	7003.9	2017	Stalling	1817.8	2.65%
Telangana	South	48.4	6525.8	2017	Stalling	3131.1	6.42%
Karnataka	South	39.5	12332	2017	Stalling	5684.5	11.42%
Himachal Pradesh	North	37.5	36.5	N/A			
Bihar	East	33.8	155.2	Pre-takeoff	N/A		
Jharkhand	East	27.2	53.7	Pre-takeoff	N/A		
Punjab	North	22.8	1702.6	2017	Stalling	599	2.26%
Jammu & Kashmir	North	17	9.4	N/A			
Haryana	North	14.9	163	Pre-takeoff	N/A		
Uttarakhand	North	14.3	337	Pre-takeoff	N/A		
Sikkim	East	10.9	0	N/A			
Tripura	North-East	7	6	N/A			
Kerala	South	6.7	270.2	N/A			
Assam	North-East	6	12.7	N/A			
Delhi	North	5.3	186.6	N/A			

Arunachal Pradesh	North-East	3.4	1.6	N/A
Meghalaya	North-East	1.1	0	N/A
Manipur	North-East	0.6	7.7	N/A
Ladakh	North	0.4	N/A	N/A
Nagaland	North-East	0.2	0	N/A
Mizoram	North-East	0.2	2.5	N/A
Puducherry	South	0.2	6.4	N/A
Andaman & Nicobar Islands	East	0.1	35	N/A
Goa	West	0	1.3	N/A
Chandigarh	North	N/A	10.1	N/A
Daman & Diu and Dadra & Nagar Haveli	West	N/A	41.5	N/A
Lakshadweep	South	N/A	0.4	N/A

4.2.5. Sensitivity analysis

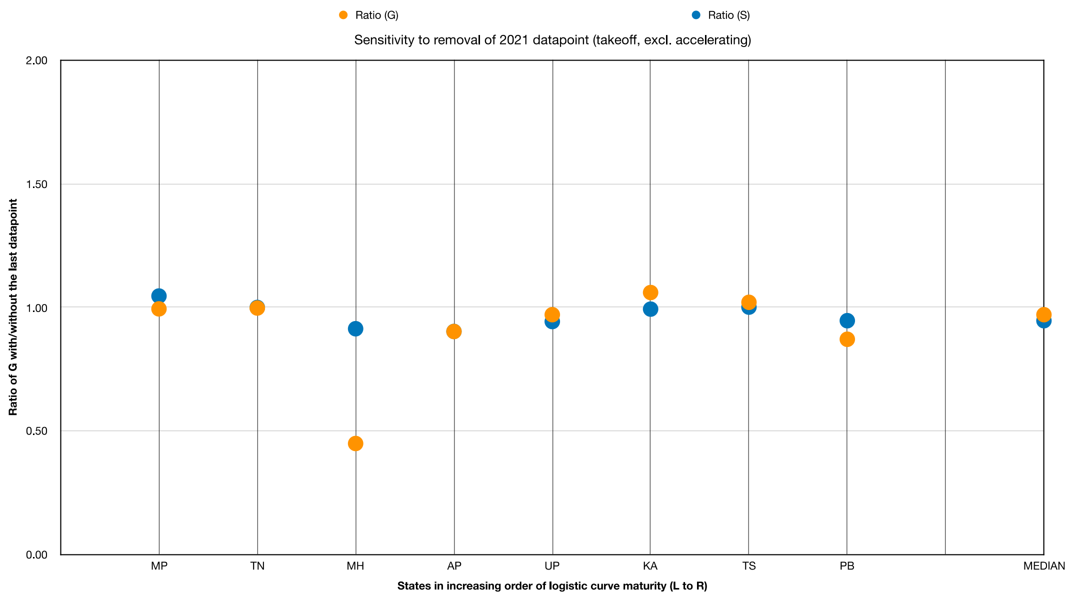

Figure 7. Sensitivity of G to the removal of the 2021 datapoint.

Figure 7 illustrates the ratios of the values of G generated by the logistic and Gompertz models with and without the 2021 datapoint. The values of G were robust to the removal of the last datapoint with median variations of 3% and 2% for the logistic and Gompertz model outputs respectively.

4.3. Measuring the effect of takeoff year on growth rates and regression analysis of growth rates

There was no difference in maximum growth rates between earlier and later adopters of solar power. The linear regression analyses revealed no statistically significant relationship between the takeoff year and G% in case of both logistic and Gompertz models. However, there was a significant negative relationship between duration of transition and takeoff year for both logistic and Gompertz models ($p<1\%$), indicating that later adopters have statistically shorter transition durations (Figure 8).

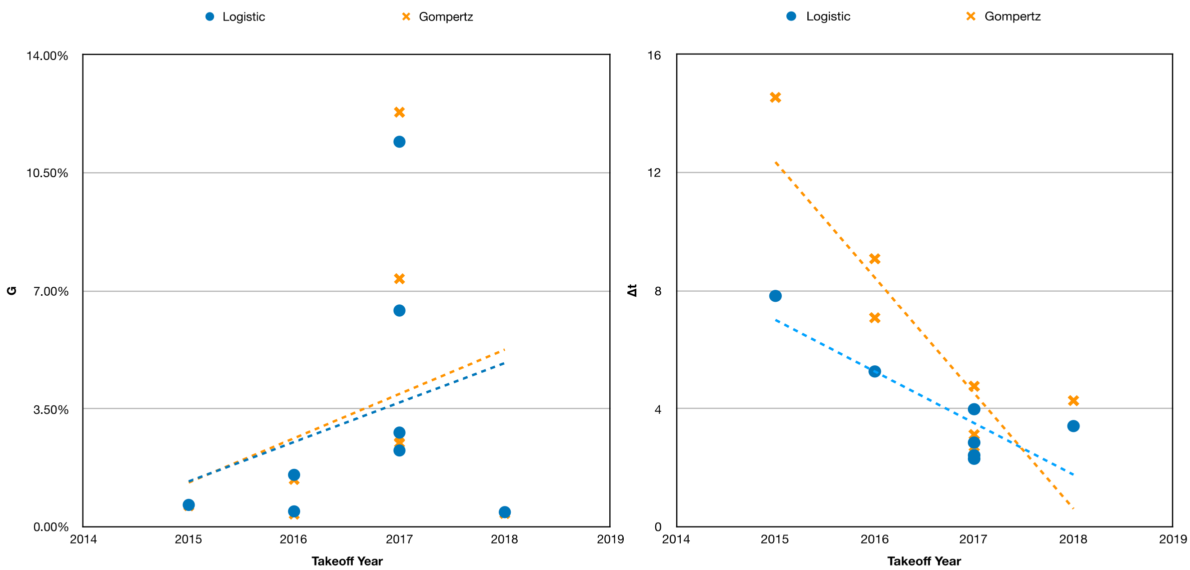

Figure 8. The relationship between takeoff year and G, Δt.

The results of the pair-wise linear regressions and the Pearson' product-moment correlation analyses run with ΔT as the dependent variable and the set of independent variables used in the regression analysis for takeoff are listed in Table 13.

Table 13. Analysis of the factors influencing Δt.

Independent Variable	Logistic				Gompertz			
	Pearson's r	**p-value**	**R^2**	**p-value**	**Pearson's r**	**p-value**	**R^2**	**p-value**
Takeoff year	-0.66	**0.04**	0.73	**0.01**	-0.86	**0.01**	0.75	**0.01**
Per capita state GDP	-0.23	0.29	.01	0.81	-0.12	0.39	0.01	0.78
Change in power demand	0.01	0.50	0.09	0.47	0.23	0.29	0.07	0.51
Total electricity supply	0.26	0.27	0.08	0.49	0.30	0.24	0.09	0.47
Ease of Doing Business score	0.27	0.26	0.21	0.25	0.46	0.13	0.02	0.71
Solar power generation potential	0.43	0.14	0.41	0.09	0.70	**0.03**	0.49	0.05
Average GHI	-0.32	0.22	0.01	0.78	0.07	0.43	0.01	0.86
Coal transportation costs	0.27	0.26	0.01	0.83	-0.05	0.46	0.00	0.91
Average DISCOM rating	-0.26	0.27	0.05	0.59	-0.17	0.34	0.03	0.69
Average energy balance	0.24	0.28	0.14	0.37	0.37	0.18	0.14	0.37
Solar power purchase tariffs	-0.66	**0.04**	0.31	0.15	-0.44	0.14	0.19	0.28

With the exception of the takeoff year (strong negative relationships for both the logistic and Gompertz values), statistically significant correlations were found between the logistic ΔT and solar power purchase tariffs (a moderately strong negative relationship), and between the Gompertz ΔT and total solar power generation potentials (a moderately strong positive relationship).

The outcomes for the same exercise performed for G% values is presented in Table 14.

Table 14. Analysis of factors influencing G.

Independent Variable	Logistic				Gompertz			
	Pearson's r	p-value	R^2	p-value	Pearson's r	p-value	R^2	p-value
Takeoff year	0.28	0.25	0.08	0.50	0.28	0.25	0.08	0.50
Per capita state GDP	0.10	0.41	0.01	0.82	0.09	0.41	0.01	0.83
Change in power demand	0.12	0.39	0.00	0.95	0.16	0.35	0.00	0.99
Total electricity supply	-0.44	0.14	0.19	0.27	-0.45	0.13	0.20	0.27
Ease of Doing Business score	-0.16	0.36	0.02	0.71	-0.18	0.33	0.03	0.66
Solar power generation potential	-0.38	0.18	0.14	0.35	-0.39	0.17	0.15	0.34
Average GHI	0.42	0.15	0.18	0.30	0.40	0.16	0.16	0.33
Coal transportation costs	-0.32	0.22	0.01	0.45	-0.35	0.20	0.12	0.40
Average DISCOM rating	0.24	0.29	0.06	0.57	0.24	0.28	0.05	0.56
Average energy balance	-0.01	0.49	0.00	0.99	-0.01	0.49	0.00	0.98
Solar power purchase tariffs	0.80	**0.01**	0.65	**0.02**	0.82	**0.01**	0.67	**0.01**

The only statistically significant relationship identified was between G% and the solar power purchase tariffs (a strong positive relationship). This relationship was significant for both the logistic and Gompertz model outputs and identified in both the linear regression as well as the Pearson's product-moment correlation analyses.

4.4. Measuring the feasibility of JN-NSM targets

4.4.1. National targets

2022 JN-NSM target

Capacity

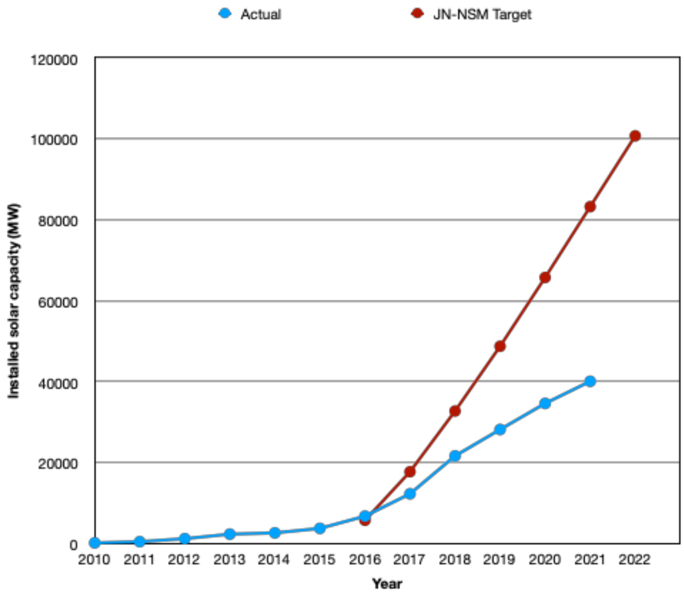

Figure 9. Actual solar capacity installation versus the JN-NSM targets.

Figure 9 illustrates that the actual solar capacity installation has consistently lagged behind the annual targets set under the JN-NSM, which planned to have 100 GW of installed solar power generation capacity by 2022. Table 15 outlines the year-on-year performance of the country.

Table 15. Actual and target installed capacity for the 2022 target.

Year	Actual installed solar capacity (MW)	Actual annual addition (MW)	% annual growth	Target installed solar capacity (MW)	Targeted annual addition (MW)	Targeted % annual growth	Annual deficit (MW)	Total installed capacity (MW)
2010	161			Pre JN-NSM period				159398
2011	461	300	0.19%					173626
2012	1205	744	0.43%					199877
2013	2319	1114	0.56%					223344

2014	2632	313	0.14%					248554
2015	3744	1112	0.45%					274904
2016	6763	3019	1.10%	5744	2000	0.73%	1019	305162
2017	12289	5526	1.81%	17744	12000	3.93%	-5455	326833
2018	21651	9362	2.86%	32744	15000	4.59%	-11093	344002
2019	28181	6530	1.90%	48744	16000	4.65%	-20563	356100
2020	34628	6447	1.81%	65744	17000	4.77%	-31116	370106
2021	40085	5457	1.47%	83244	17500	4.73%	-43159	382151
2022				100744	17500			

It is evident that the growth rates for capacity have consistently fallen below the rates that would have been required to meet the targets. This contributed to an increasing deficit between the target and actual installed capacities. In addition to the planned capacity addition of 17,500 MW for 2021-2022, as of March 2021, there was a capacity backlog of 43,159 MW which also needs to be recouped in order to reach 100 GW capacity in the next year. Thus, India will need to install a total capacity of 60,659 MW in one year, which is 1.5 times its total installed capacity as of March 2021, and close to 10 times the average annual capacity additions over the last three years.

The growth trajectories obtained by fitting the actual installed capacity data and the JN-NSM targets to the logistic, Gompertz, and log-linear models are illustrated in Figure 10.

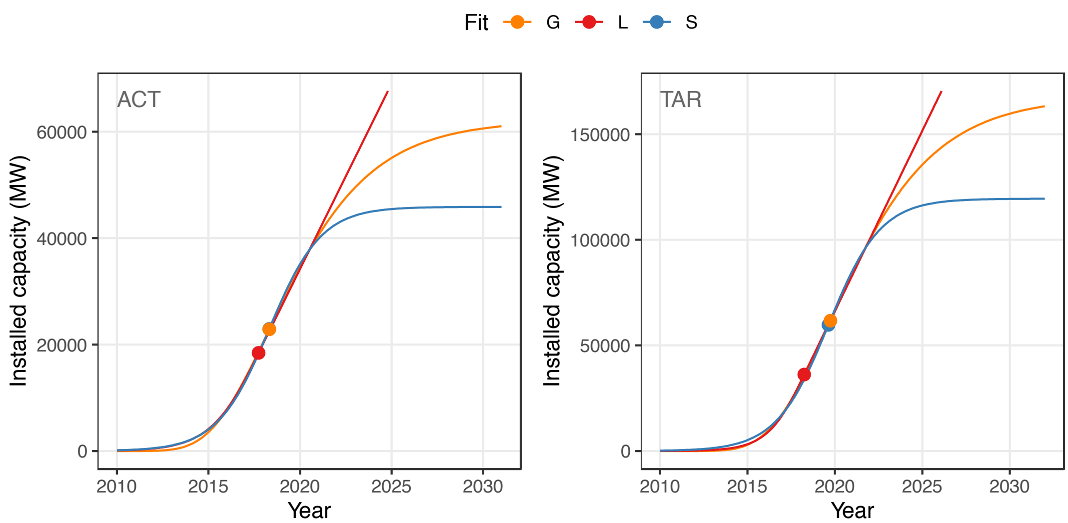

Figure 10. Growth curves for actual versus target capacity under the JN-NSM.
(G = Gompertz, L = Log-linear, S = Logistic)

The growth parameters estimated from the three models for the two data are presented in Table 16. It is clear that the growth rates (in both absolute and percentage terms) from the empirical data are less half those for the models fit to the JN-NSM targets. The remaining target deficit is about eight times greater than the maximum annual growth rates from all three models. Moreover, comparisons between the model asymptotes and the 100 GW target reveal that the latter is 1.6-2.7 times larger than the former. In fact, the deficit is larger than the maximum G values for the target data itself.

Table 16. Model-wise growth parameters and target feasibility assessment for 2022 capacity target.

Model	**Actual capacity installed upto March 2021**					**JN-NSM Targets**				
	L (GW)	**G (GW/yr)**	**G%**	**Deficit/G**	**Target/L**	**L (GW)**	**G (GW/yr)**	**G%**	**Deficit/G**	**Target/L**
Logistic	45.9	8.1	2.35%	7.52	2.18	119.4	20.0	5.39%	3.04	0.84
Gompertz	62.1	7.2	2.10%	8.38	1.61	167.7	18.2	4.91%	3.34	0.60
Log-linear	36.9	7.0	2.03%	8.71	2.71	72.4	17.1	4.97%	3.55	1.38

Generation

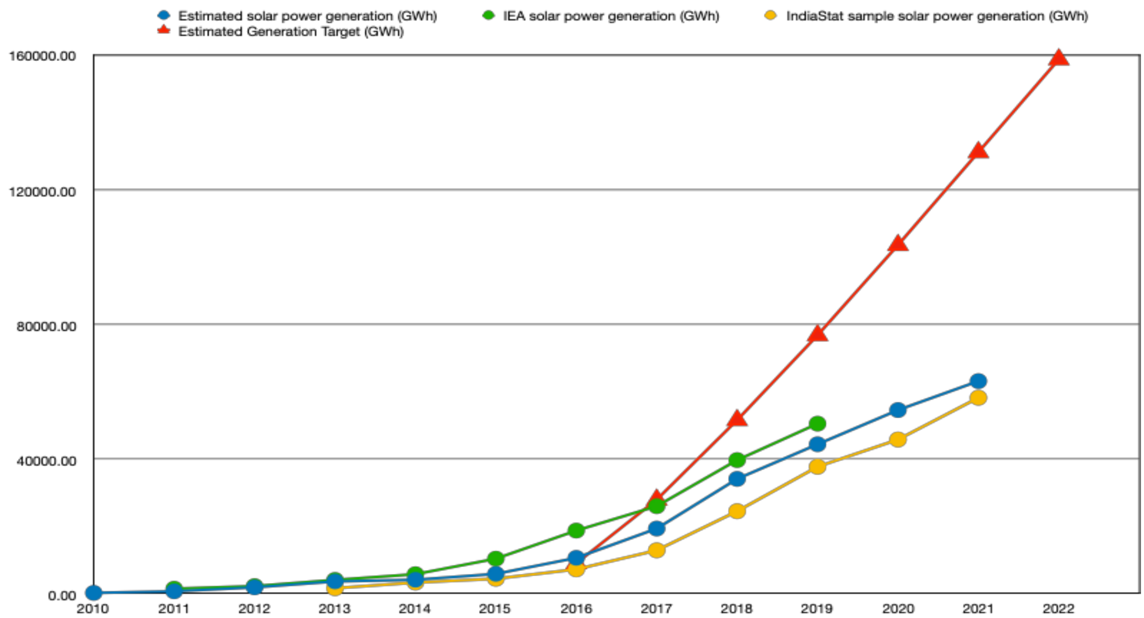

Figure 11. Actual solar power generation versus the targets estimated from the JN-NSM targets.

Figure 11 illustrates that the actual solar power generation has consistently lagged behind the targets estimated from the JN-NSM capacity targets. This trend is the same irrespective of the generation data used for comparison; here, I use national-level IEA solar power generation data from 2010-2019, IndiaStat and CEA-CEEW data from 2013-2021, as well as generation estimated from the actual installed solar power capacity data from 2010-2021. Table 17 further expands on the year-on-year performance observed thus far.

Table 17. Actual and estimated target generation for the 2022 target.

Year	Solar power generation (GWh)			Annual growth in generation (GWh)			Estimated Generation Target (GWh)	Gaps between actual and target generation (GWh)		
	Estimated	IEA	Analysis sample	Estimated	IEA	Analysis sample		Estimated	IEA	Analysis sample
2010	254									
2011	727	1494		473						
2012	1900	2271		1173	777					
2013	3657	4111	1649	1757	1840				Pre-JNNSM period	
2014	4150	5812	3331	493	1701	1683				
2015	5903	10420	4461	1753	4608	1129				
2016	10664	18778	7264	4760	8358	2804	9057.14	-1606.76	-9720.86	1792.76
2017	19377	26035	12908	8713	7257	5643	27978.74	8601.44	1943.74	15071.08
2018	34139	39728	24536	14762	13693	11628	51630.74	17491.44	11902.54	27094.57
2019	44436	50557	37759	10296	10828	13223	76859.54	32423.74	26302.89	39100.09
2020	54601		45837	10166		8077	103665.14	49063.71	103665.14	57828.38
2021	63206		58266	8605		12429	131259.14	68053.11		72993.51
2022							158853.14			

Irrespective of the data source, the gaps between the empirical generation figures and the estimated targets have continued to widen over time, and as of 2021, were as large or larger than the total solar power generation in 2021 itself.

Figure 12 illustrates the respective logistic, Gompertz, and log-linear growth curves for the empirical generation data and the estimated targets.

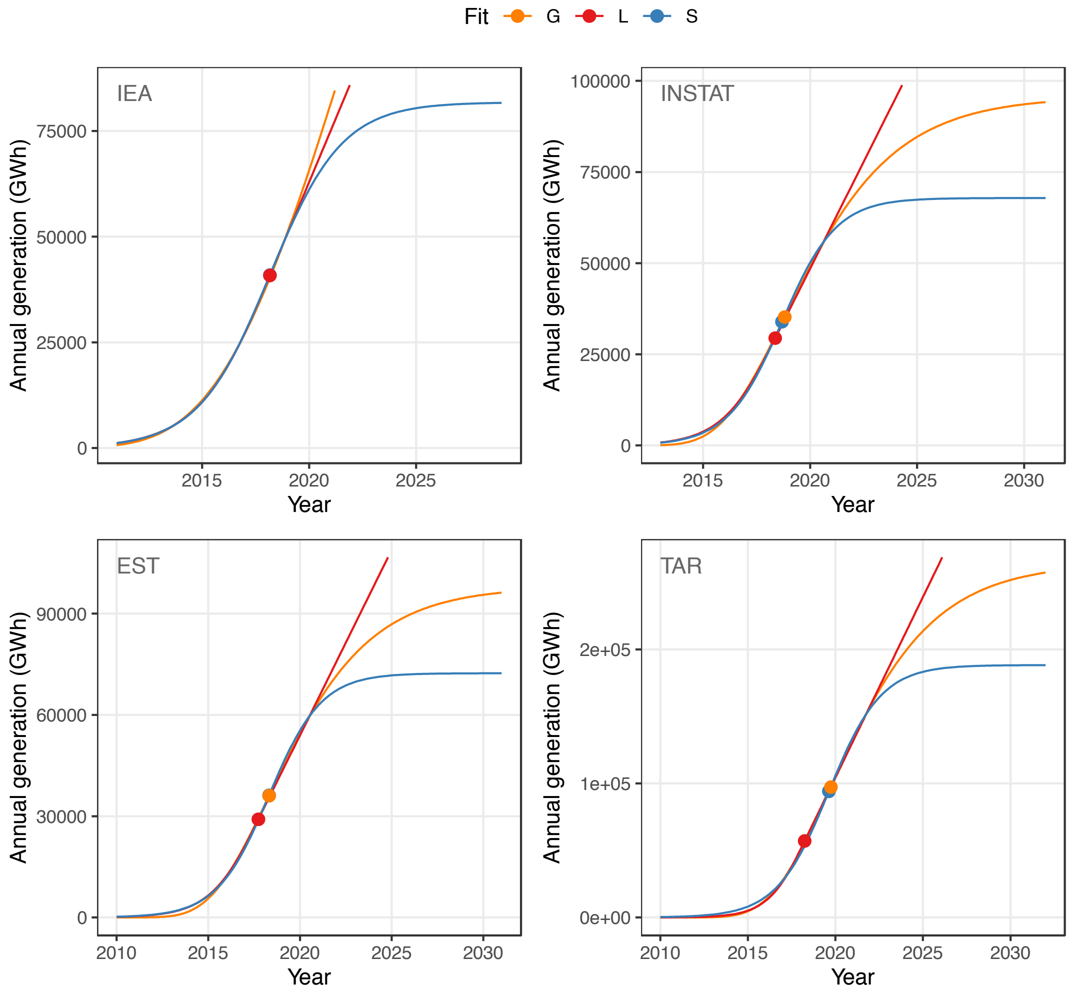

Figure 12. Growth curves for different generation data and target estimated from the JN-NSM capacity target.
(G = Gompertz, L = Log-linear, S = Logistic)

I chose to not use the growth parameters estimated from the IEA data as it is not as recent as the other two. From Table 18, it is clear that the growth rates as well as saturation values from all three models for both the estimated and actual generation data upto 2021 are almost identical. Though it was expected for the results for the estimated generation data to be the same as that capacity targets, the gap between the estimated target for 2022 and the actual generation in 2021 is also 7.5-8.6 times larger than the estimated maximum annual growth rates.

An interesting difference that can be observed between the generation and capacity analyses is the difference in the percentage G values – while those for capacity installation were between 2-2.3%, the ones for generation are in a much lower 0.74-0.86% bracket. However, in both cases, the estimated maximum annual growth rates are less than half the rates estimated by the model fits for the target data (which are in the 1.81-1.97% range for the estimated generation target).

Comparing the model asymptotes to the target reveals that the targets are between 1.6-2.7 times greater than the saturation levels estimated by the models based on the empirical data. The gap between the actual and target generation figures is over three times larger than the maximum growth rates estimated by different models fit to the estimated target data.

Table 18. Model-wise growth parameters and target feasibility assessment for 2022 generation target.

Model	**Estimated**					**Analysed**					**Target**				
	L (TWh)	**G (TWh/yr)**	**G%**	**Gap/G**	**Tar./L**	**L (TWh)**	**G (TWh/yr)**	**G%**	**Gap/G**	**Tar./L**	**L (TWh)**	**G (TWh/yr)**	**G%**	**Gap/G**	**Tar./L**
Logistic	72.3	12.7	0.86	7.52	2.20	67.9	13.4	0.87	7.50	2.34	188.3	31.5	1.97	3.12	0.84
Gompertz	98	11.4	0.77	8.38	1.62	95.7	11.9	0.77	8.43	1.66	264.4	28.6	1.79	3.43	0.60
Log-linear	58.1	11	0.74	8.71	2.73	58.9	11.7	0.79	8.60	2.70	114.2	26.9	1.81	3.64	1.39

2027 (200 GW) and 2030 (300 GW) targets

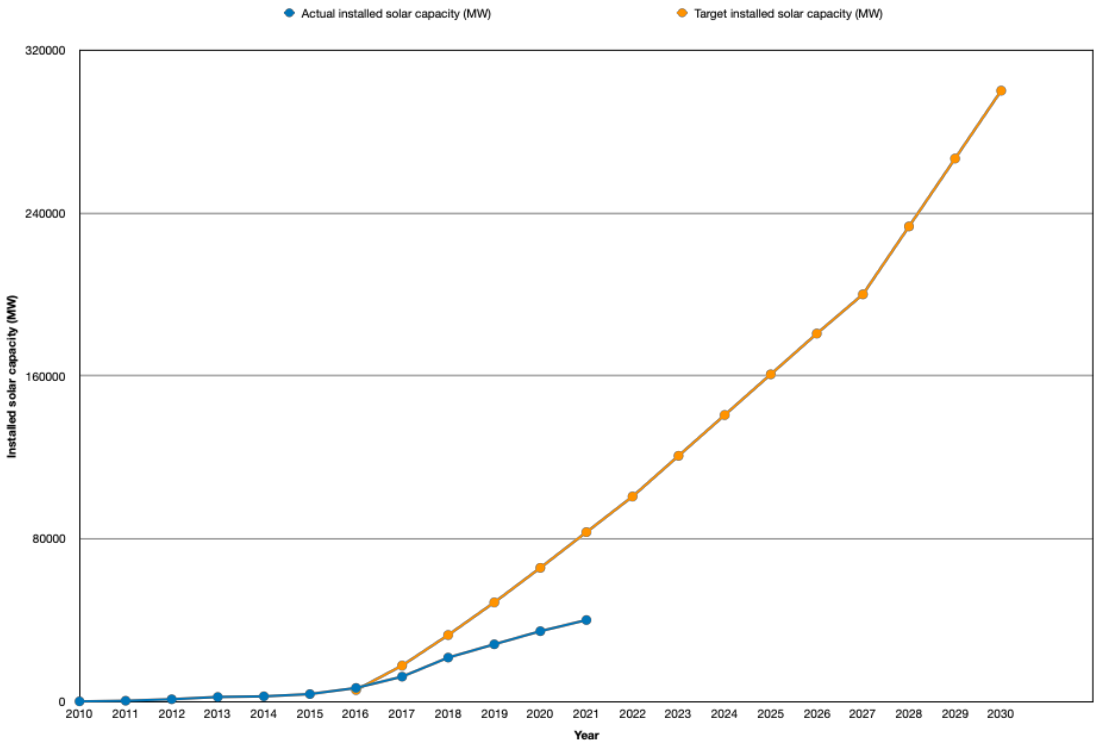

Figure 13. Actual solar capacity installation versus the roadmap for the 2027 and 2030 'soft' targets

Figure 13 highlights the roadmap to the 2027 and 2030 targets that plan to expand the total installed solar power generation capacity from 100 GW in 2022 to 200 GW and 300 GW respectively. The actual solar capacity installed upto 2021 is also illustrated. In order to meet the additional targets, average capacity additions of 20 GW per year between 2022-2027, followed by 33 GW per year between 2027-2030 will be required.

Figure 14 illustrates the curves for the three growth models fit to the actual installed capacity data until 2021 with the 2022, 2027, and 2030 targets added as additional datapoints. It also shows the growth curves for the 2027 and 2030 targets added to the JN-NSM annual targets.

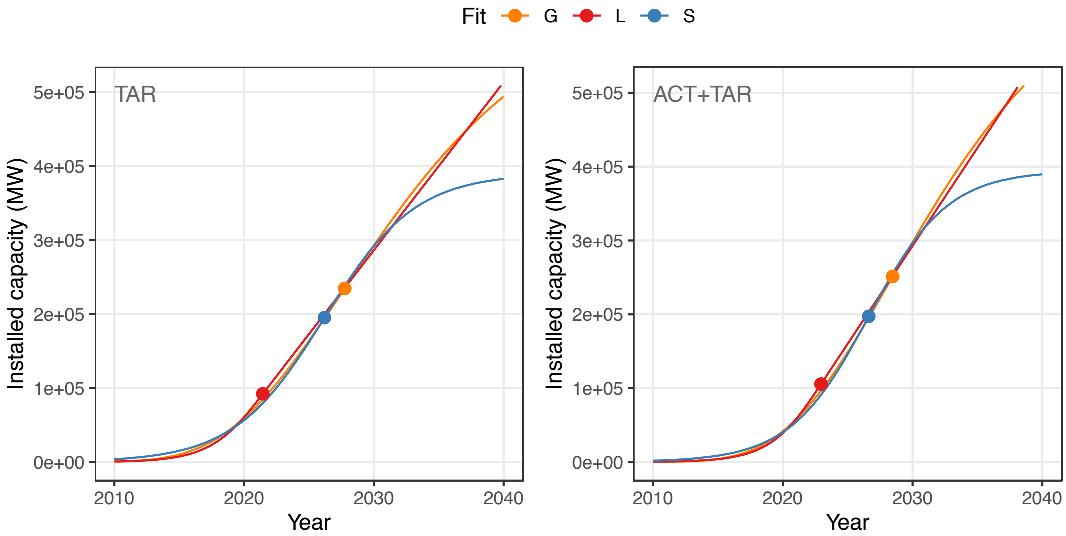

Figure 14. Model fits generated for the 2027 and 2030 targets.
(G = Gompertz, L = Log-linear, S = Logistic)

Table 19 highlights the growth parameters for the models fit to the target data and compares them to those fit on the actual capacity installation upto March 2021. The deficit between the installed capacity in 2021 and the 2030 target was annualized by dividing it by nine years. This annualized deficit was found to be 3.6-4.15 times the maximum growth annual growth rates from the empirical data model fits. For the ideal case building on the 2022 target, the model estimates a maximum annual growth rates as high as 28 GW per year, which is still less than the annualized deficit. On considering the actual capacity installed upto March 2021, the required maximum annual growth rate shoots up to 32.4 GW per year, which is 4-5 times greater than the estimate for the actual data.

Table 19. Model-wise growth parameters and feasibility assessment for 2027 and 2030 targets.

Model	2022, 2027 and 2030 targets with actual data upto March 2021					2027 and 2030 targets with the JN-NSM targets				
	L (GW)	G (GW/yr)	G%	Annualised Deficit/G	Target/L	L (MW)	G (MW/yr)	G%	Annualised Deficit/G	Target/L
Logistic	394.4	32.4	N/A	0.89	0.76	390.1	28.0	N/A	1.03	0.77
Gompertz	682.7	30.5	N/A	0.95	0.44	637.7	26.1	N/A	1.11	0.47
Log-linear	210.9	26.5	N/A	1.09	1.42	184.2	22.7	5.94%	1.27	1.63

4.4.2 State-level targets

Capacity

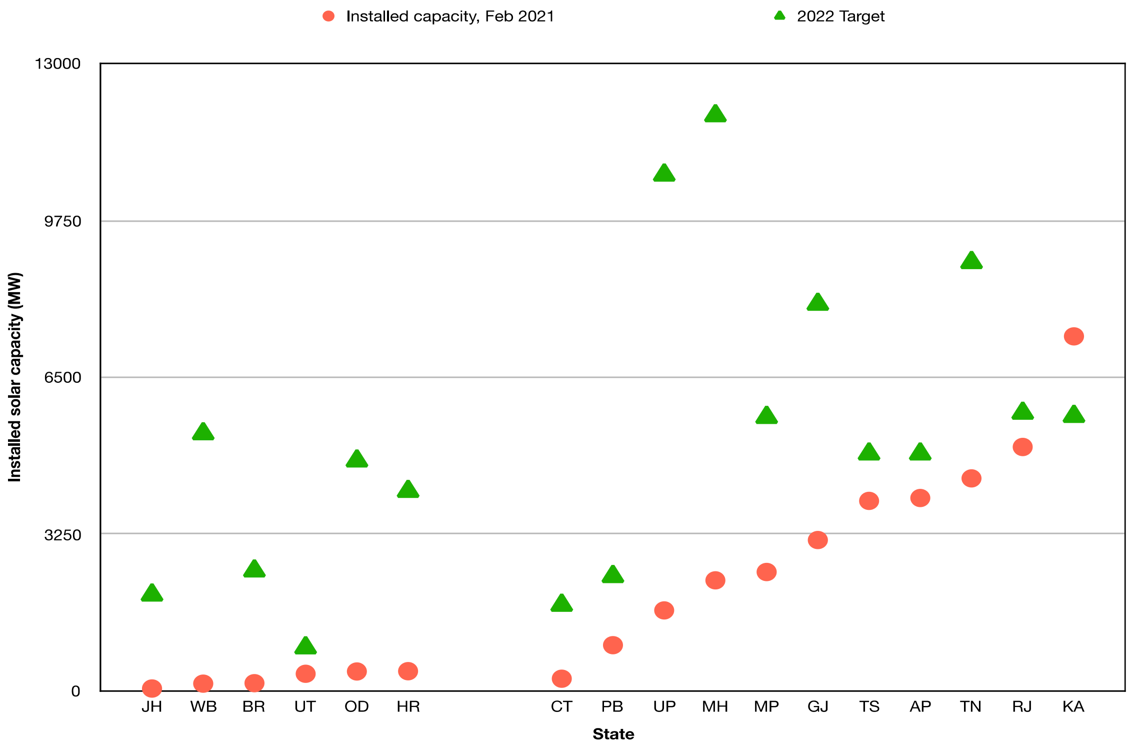

Figure 15. State-wise actual installed solar capacity in February 2021 versus JN-NSM targets.

Figure 15 illustrates the individual JN-NSM solar capacity installation targets for states in my analysis sample along with the actual installed solar capacity as of February 2021. The cluster on the left includes states where solar has not achieved takeoff while the ones on the right are in the post-takeoff stage.

Table 20 lists the installed capacity as of 2021, the 2022 targets, and the deficits between the two. This deficit is then compared to the average annual capacity addition observed between 2019-2021. Karnataka is the only state that had already achieved its JN-NSM target, and installed an additional 1650 MW of solar capacity. Of the remaining states, Rajasthan is the only state where the ratio between the deficit and the three-year average growth rate is close to one; for the rest of the takeoff states, this ratio ranges from 3 in case of Andhra Pradesh to 217 in case of Chhattisgarh. The variation is even larger in case of the pre-takeoff states, with the ratio ranging from 35 in case of Uttarakhand to over 1876 in Odisha.

Table 20. State-wise feasibility assessment for 2022 capacity targets.

State	Installed capacity 2021 (MW)	2022 Target (MW)	Deficit (MW)	Deficit as % of 2021 capacity	3 Year Avg. Annual Capacity Addition	Deficit/Avg.
CT	252	1783	1531	606.19%	7.04	217.30
GJ	3125	8020	4895	156.63%	337.24	14.51
RJ	5054	5762	708	14.02%	660.38	**1.07**
AP	3997	4917	920	23.03%	303.61	3.03
PB	947	2377	1430	150.98%	13.83	103.42
TS	3936	4917	981	24.91%	114.76	8.55
KA	7347	5697	**-1650**	N/A	417.10	N/A
MP	2463	5675	3212	130.39%	207.69	15.46
MH	2290	11926	9636	420.79%	218.81	44.04
TN	4403	8884	4481	101.75%	609.42	7.35
UP	1668	10697	9029	541.50%	235.80	38.29
				Pre-takeoff		
BR	160	2493	2333	1462.91%	5.69	410.34
HR	408	4142	3734	915.62%	61.10	61.11
JH	49	1995	1946	4002.41%	4.56	426.84
OD	402	4772	4370	1087.89%	2.33	1875.66
UT	353	900	547	154.66%	15.55	35.14
WB	150	5336	5186	3461.13%	24.63	210.56

Generation

Figure 16. State-wise actual solar power generation in February 2021 versus targets estimated from the JN-NSM targets.

Figure 16 illustrates the estimated generation targets for each state along with their corresponding actual generation numbers for 2021. The cluster on the left includes states where solar has not achieved takeoff while the ones on the right are in the post-takeoff stage.

Table 21 lists these figures and the observed average annual growth in generation between 2019-2021 along with the gaps between the target and the actual generation. The maximum annual growth rates and asymptote values for stable and stalling growth states are also listed. The gap is compared against the three-year average and model output growth rates. Further, the target is compared to the saturation values estimated by the models for the applicable states.

Karnataka is the only state that has already surpassed its estimated target; it had generated 3349 GWh over and above its 2022 target in 2021. This is also reflected in its Target/L ratio, which was found to be about 0.7 for the logistic and Gompertz model fits. Andhra Pradesh was the only state where the growth rate observed over the last three years was greater than the estimated target (Gap/3YA ratio of 0.77). On looking at the models' G values, I found that aside from Andhra

Pradesh, Telangana was the only state where the gap to the target was smaller than the maximum annual growth rates. The Target/L ratio for these two states was also found to be in the 1.02-1.18 range. The Gompertz model asymptote for Madhya Pradesh was also found to be larger than the target yielding a Target/L ratio of 0.93.

For the remaining states, the respective gaps were found to be between 2.3 (in case of Rajasthan) to over 44.2 (in case of Uttar Pradesh) times the three-year average growth rates for the takeoff states, while for the pre-takeoff states the variation was much larger (69-1145 times). With the exception of Andhra Pradesh, Karnataka, and Telangana, the Gap/G ratio for the logistic and Gompertz models. ranged from 3.4-36 for the stable and stalling states. The Target/L ratio for this set of states was found to range between 1.6 (Madhya Pradesh) to 9.8 (Uttar Pradesh) in case of the logistic and Gompertz models. The same trends were observed for the log-linear model outputs, but the ratios were much larger.

Table 21. State-wise feasibility assessment for 2022 generation targets.

State	Actual solar power generation 2021 (GWh)	2022 Estimated Generation Target (GWh)	Generation gap (GWh)	3 Year Avg. annual growth (GWh)	Gap/3YA	Fit	G (GWh)	L (GWh)	Gap/G	Target/L
CT	670	2811	2142	57.38	37.33					
GJ	9976	12646	2670	790.43	3.38					
RJ	4420	9086	4666	2010.41	2.32					
						S	1925	6961	**0.39**	**1.11**
AP	7004	7753	749	974.92	**0.77**	G	1814	7630	**0.41**	**1.02**
						L	1413	1329	**0.53**	5.83
						S	599	1552	3.41	2.42
PB	1703	3748	2045	90.18	22.68	G	580	1595	3.53	2.35
						L	259	347	7.89	10.79
						S	3131	6543	**0.39**	**1.18**
TS	6526	7753	1227	832.42	1.47	G	3194	6656	**0.38**	**1.16**
						L	1359	1864	**0.90**	4.16
KA	12332	8983	**-3349**	3313.41		S	5684	12507		**0.72**

						G	5493	13159		**0.68**
						L	3352	4751		1.89
						S	787	5600	5.93	1.60
MP	4283	8948	4665	634.39	7.35	G	751	9636	6.21	**0.93**
						L	736	4966	6.34	1.80
						S	566	2709	29.12	6.94
MH	2332	18805	16473	410.50	40.13	G	456	3653	36.09	5.15
						L	448	2846	36.75	6.61
						S	1268	6093	6.63	2.30
TN	5602	14008	8406	898.81	9.35	G	1157	7220	7.27	1.94
						L	1005	1848	8.37	7.58
						S	554	1720	27.36	9.81
UP	1708	16867	15159	342.90	44.21	G	507	1906	29.90	8.85
						L	374	842	40.52	20.04
				Pre-takeoff						
BR	155	3931	3770	3.29	1144.87					
HR	163	6531	6430	30.59	210.18					
JH	54	3146	3129	11.43	273.63					
OD	429	7524	7173	70.09	102.34					
UT	337	1419	1052	15.29	68.82					
WB	67	8414	8350	15.43	541.05					

Chapter 5: Discussion

5.1. Solar power in India – The status quo

Over the course of the last decade, India's installed solar power generation capacity has grown from 0.16 GW in 2010 to about 40 GW in March 2021 – a growth of almost 250 times. While this is a tremendous achievement, India has set its sights on even loftier ambitions, setting targets to install 100 GW of solar capacity by 2022, and 300 GW by 2030. Given the impressive rise of solar so far, what can the past tell us about the future of the technology in the coming decade?

5.1.1. A story of unmet potential

The growth parameters estimated by fitting different growth models to national-level power generation data suggest that solar power in India is falling short of fulfilling its true potential. On studying the 11 Indian states where solar power has taken off, I found that growth was fastest between 2018-2019, with maximum annual growth rates (G) of 11-12.7 TWh/year which corresponded to about 0.77-0.87% of the total national electricity supply (depending on the growth model). Though this is faster than the median growth rate of 0.6% observed in other stable and stalling countries globally (Cherp *et al.* forthcoming), at these rates, it will take India at least 173 years to even reach the lower estimate of its solar potential.

Deshmukh *et al.* (2019) have estimated a cumulative national solar potential of 1500-5200 GW/year for utility-scale solar PV in India, which corresponds to a power generation potential of 2200-8200 TWh/year. As per my analysis, solar power has crossed the point of inflection on the growth curve, and is currently undergoing a phase of 'stable' growth with annual growth rates close to, but smaller than G. If growth continues to slow down further in line with current trends, the models estimate that solar power will saturate at an estimated annual generation ceiling of 58-72 TWh. This is less than 3% of the estimated potential and two orders of magnitude smaller. Similar results are observed for the growth parameters estimated by models fit to the installed capacity data; while the maximum growth rates are much higher (between 2-2.35% of the total installed power generation capacity), the estimated ceilings in the 37-62 GW range are again, two orders of magnitudes smaller than the estimated potential.

At first glance, the slowing national growth could be explained by the fact that solar power has completed the formative phase of the technology adoption cycle in only a handful of Indian states. As of March 2021, solar power had achieved takeoff in just 11 of India's 28 states and 8 union territories (UTs). Most of these 11 states lie in the western and southern parts of the country, and together accounted for 99% of the country's total solar powered electricity generation in 2021. However, though these 11 states constitute a minority in the numerical sense, they generate close to 70% of India's total electricity. Thus, the reason behind the slowing national growth rate is not simply the absence of takeoff in the other states, but also what is happening within the states where solar has already taken off.

5.1.2. Spatial diffusion and uneven growth

My analysis shows that as a technology, solar power diffused from the 'core' of Gujarat and Rajasthan (takeoff in 2013 and 2014 respectively) in the western/north-western region, to the 'rim' of other western states (Madhya Pradesh in 2015 and Maharashtra in 2016). From there, it spread to the 'periphery' constituted by the southern states of Tamil Nadu (takeoff in 2016), Andhra Pradesh, Karnataka, and Telangana as well as the northern state of Punjab (all four in 2017). Subsequently, solar power took off in Uttar Pradesh (north) in 2018, and then in Chhattisgarh (west) in 2021. The technology is yet to complete the formative phase in any eastern state, and is faring especially poorly in the mountainous states of the north-east. The six remaining 'pre-takeoff' states in my sample – Bihar, Haryana, Jharkhand, Odisha, Uttarakhand, and West Bengal – are all from the northern and eastern parts of the country. The sequence of takeoff and the estimated best-fit G values for these states is illustrated in Figure 17.

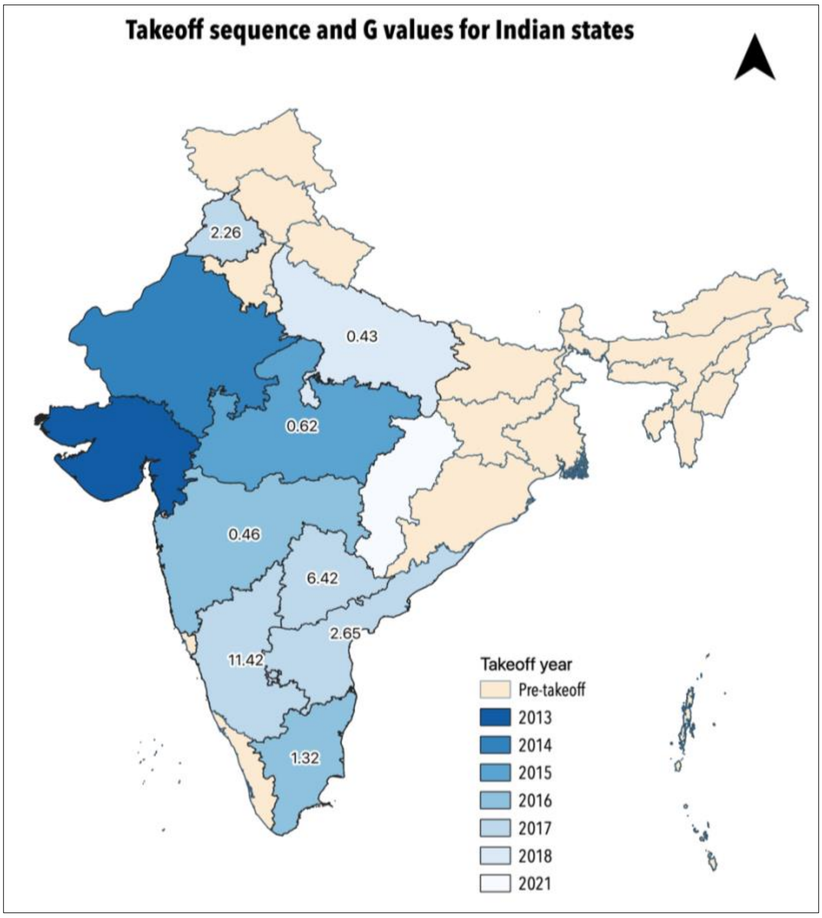

Figure 17. Takeoff sequence and maximum annual growth rates for Indian states.

Among the states where solar power has taken off, growth continues to accelerate in three states – Chhattisgarh, Gujarat, and Rajasthan. The eight remaining states, which harbor about a third of the country's total solar power generation potential, are evenly split between the 'stable' and 'stalling' growth phases.

While the maximum annual growth rates could not be reliably estimated for states in the accelerating growth phase, the median normalized G values for the stable and stalling states were 0.53% and 3.24% respectively. The median transition duration for the stable states was 5.27 years, while that for the stalling states was 2.78 years. Thus, the states with the most rapid solar power growth rates moved through the adoption cycle more quickly and were the first to slow down. Conversely, the stable states with relatively slower growth rates have been able to sustain growth for longer.

Solar power has grown the fastest in Karnataka, with a maximum annual growth rate of about 12% of the state's total power generation. However, the devil is in the details; the reason for Karnataka's incredible G value is the inauguration of the massive 2050 MW Shakti Sthala project in Pavagada, which single-handedly accounts for about 30% of the state's installed solar capacity. It's average growth rate over the last three years is almost half its G value, demonstrating that such high growth rates are outliers which are unsustainable in the longer run. This finding is also echoed in the case of Telangana, where the annual growth rate peaked at about 7% in 2017, and has since dropped to an average of 1.7% over the last three years. Both of these states have had short transition durations, and are in the stalling growth phase now. The neighboring state of Tamil Nadu has showcased a slower, but more sustainable growth which could serve as a better model for other states. It achieved a maximum annual growth rate of 1.32% and has continued to grow at an average rate of 1% over the last three years, which is faster than the national G values.

As opposed to Busby and Shidore (2021) who classify states as Achievers, Middlers, Laggards, and Marginals on the basis of the share of utility-scale solar in their peak demand, I have used the states' respective growth curve maturities to categorize them into pre-takeoff and (post) takeoff states, with the latter being further decomposed into 'accelerating', 'stable', and 'stalling' growth phase states. On comparing the outcomes of the two classifications, I find that their set of Marginals exactly corresponds to my set of pre-takeoff states (with the addition of Odisha and Uttarakhand, which they classify as Laggards). My 'takeoff' states correspond to a superset of all their Achievers, Middlers, and some of their Laggards. My categorization is generally more dynamic and allows for changing the status of the states as they move into other phases of the growth curve.

5.2. Drivers of solar power growth and inter-state differences

5.2.1. Why do some states achieve takeoff and others don't?

This thesis finds that the incidence of takeoff in a particular state correlates with three variables – its average global horizontal irradiance (GHI), the cost of coal transportation, and its Ease of Doing Business (EBD) score. The first of these is a measure of the abundance of a state's solar energy resource. Its relationship with greater solar deployment explains why the technology has primarily taken off in the western and southern states – these are the regions where most of India's solar potential is concentrated (Deshmukh *et al.* 2019). The second variable corresponds to a more economic concern i.e., the cost of thermal power generation, while the EBD score serves as a proxy for the state's attractiveness to private investment in solar power. Thus, solar power has achieved takeoff in states with more abundant solar resources, more expensive thermal power, and a more favorable business environment.

Two of these factors – high solar irradiance and high coal costs – are in agreement with Busby and Shidore (2021), but contrary to their findings this thesis did not identify significant relationships between solar takeoff and the condition of power distribution companies (DISCOMs), and the states' power deficits. Its findings also differ from the view of Shrimali *et al.* (2020) who suggested that greater state wealth corresponds to higher levels of solar deployment.

5.2.2. Why do states achieve takeoff when they do?

I found that a state's total solar power generation potential was the only factor that influenced the takeoff timing in a statistically significant manner – the greater the overall solar potential of a state, the earlier the takeoff of solar power. I also identified that the initial solar power purchase tariff influenced the takeoff timing, albeit with a lower statistical significance; it is quite possible that the tariffs are themselves correlated with the solar potential. Thus, this finding warrants skepticism and closer future analysis. Nonetheless, it supports the larger idea that solar power underwent more dynamic growth in states where there was a stronger financial incentive for agents to make investments in the technology. In sum, my findings suggest that the overall abundance of the solar resource, and a greater financial incentive to invest in harnessing it were the primary factors that led to earlier solar takeoff in some Indian states as opposed to others.

5.2.3. What happens if some states adopt solar power at scale earlier than others?

My analysis of the relationship between the takeoff year, maximum annual growth rates (G), and transition durations found that the duration of transition is statistically shorter for states with later solar power takeoff. Simultaneously, I found no significant relationship between the takeoff year and G. The idea that later adopters benefit from the experience of early adopters is quite prevalent in the technology diffusion literature (Wilson *et al.* 2013, Grubler 1990) with Grubler (1996) suggesting significantly faster adoption rates can be observed in later adopters. Taken together, my two findings for solar power in India suggest that while later adopters may move through the technology adoption cycle faster, they do not necessarily achieve higher growth rates in the process. This may be because the reason why these systems adopt a technology later in the first place is a lack of conditions suitable for the deployment of the technology at scale. Thus, the perceived benefits of learning from the experience of early adopters may be partially cancelled out by socio-economic, political, or geophysical limitations.

5.3. Assessing the feasibility of targets

5.3.1. Is India on-track to meet its national solar capacity targets?

It appears highly unlikely that India will meet its target to install 100 GW of solar power capacity by 2022 as part of the JN-NSM. On analyzing the roadmap for the national target, it is clear that the government expected solar power to grow linearly with annual additions gradually increasing over the mission cycle. Connecting this to the classical diffusion literature, the roadmap assumes that India will remain on the earlier phases of the S-curve of technology adoption, where growth accelerates continuously. My findings suggest that this is not the case for solar power in India, which has already moved beyond the formative phase.

The logistic and Gompertz model fits for the annual targets under the JN-NSM estimate a required maximum annual growth rate of 18-20 GW of solar capacity per year. However, empirical capacity addition data reveals that the actual annual installations have consistently fallen short of the annual targets since 2017. Estimates based on empirical observations of capacity installation over the last decade suggest that the actual growth has been less than half the rates required to meet the targets. It is also telling that the growth ceilings estimated by the models are close to half the 100 GW target. In sum, my findings demonstrate that the target was quite ambitious to start with, and with a cumulative deficit of about 61 GW to overcome in the next year, it is highly unlikely that India will fulfil its JN-NSM target for 2022. It is worth noting that rooftop solar (4 GW out of 40 GW target installed as of March 2021) is responsible for much of the shortfall, with utility-scale solar (~36 GW installed capacity as of March 2021) being much closer to its target (60 GW by 2022) in comparison.

The growth trajectory of solar power observed thus far doesn't generate a lot of optimism for the feasibility of India's 2027 and 2030 'soft' targets either. Had the country been on track to achieve the 2022 target, it would have required a maximum annual growth rate of about 22.7 GW per year in order to have a cumulative solar capacity of 200 GW by 2027, and 300 GW by 2030. However, achieving these targets given the actual capacity installed as of March 2021 will require a significantly higher maximum growth rate of close to 32.4 GW per year. To provide a sense of scale, the total solar capacity India has managed to install since the beginning of the 2010s is 40 GW with maximum annual growth rates between 7-8 GW per year. Converted to annual generation growth and normalized to India's total power generation in 2021, these imply a growth rate of over 3%. These rates are unprecedented in any large country in the world, with the world's largest electricity systems with annual generation >1000TWh (e.g. the EU, China, and the US) have never exceeded 1%. The only exception is Japan, where solar power grew at a maximum rate of 1.1%. Thus, unless there is a radical departure from historical trends, it is highly unlikely that these soft targets are going to be met. Though this thesis has found that the Indian states of Karnataka and Telangana have achieved maximum growth rates faster than 3%, these states are exceptions in what is largely an underwhelming regional landscape, and their performance may be unrealizable elsewhere.

5.3.2. Are Indian states on-track to meet their targets for 2022?

My sample of 17 states accounted for 90% of the cumulative national target under the JN-NSM. As of March 2021, Karnataka was the only state that has already fulfilled its target, with Rajasthan and potentially Andhra Pradesh looking likely to be able to meet their respective targets. The remaining 14 states were well behind on their targets with the 'pre-takeoff' states performing significantly worse than their 'takeoff' group counterparts. Thus, even at the sub-national level, the growth of solar power is not on track to meet the JN-NSM targets in a majority of states. This explains the struggles with the national target. The situation is made more challenging by the fact that a disproportionately large chunk of the solar deployment till date has been concentrated in a handful of states, a majority of which are no longer in the accelerating growth phase. One could argue that the underperforming states could follow Karnataka's lead, but again, while the state's innovative land-leasing policy for solar parks was effective in driving its performance, there are questions over its replicability and long-term sustainability in other state contexts.

5.4. The road forward

In sum, my thesis finds that a handful of states, predominantly located in the western and southern part of India, house the bulk of its solar capacity and have been responsible for most of the technology's growth in the country. While the growth of solar power over the last decade has been remarkable, it is no longer accelerating, and it doesn't appear likely that it will be enough to meet the ambitious targets the Indian government has set for the future. Moreover, the growth thus far still leaves a lot of room with respect to the theoretical maximum of the country's solar potential.

Correcting this will require a massive acceleration in the deployment of solar power with large increments in annual solar capacity additions. It appears that it may be too late to salvage the 2022 targets, but in order to get on track to pursue the 2027 and 2030 targets, India needs solar power to move through the formative phase and take off in a larger number of states. Even more importantly, India needs to counter the general slowing trend that I observed in eight of the 11 states that account for 97% of India's installed solar capacity by inducing a fresh phase of accelerating growth in these states, while simultaneously sustaining growth in states where is already accelerating. The next logical question is – how?

The rapidly dropping costs of solar power are widely advertised, with the IEA's World Energy Outlook 2020 stating that in the "right conditions", it is now the "cheapest source of electricity in history" (IEA 2020). The focus then needs to be on creating these conditions. The literature on India's solar power sector highlights the key barriers to the large-scale deployment of the technology in the county. These include an uneven distribution of solar potential, a lack of domestic R&D and manufacturing, difficult land acquisition, inadequate finance and credit, corruption, and policy paralysis (see chapter 2).

My analysis identifies that there are three factors that correlate with solar power maturing beyond the formative phase in a particular state – plentiful solar irradiance, a more nurturing business environment, and expensive thermal power. While not much can be done to increase the amount of sunlight a state gets, the other two factors can serve as leverage points for future action. The Indian solar power ecosystem needs to generate the right techno-economic, socio-technical, and political incentives for the various stakeholders in the system.

My analysis of the factors influencing solar power growth finds that states with higher solar power purchase tariffs witnessed faster growth rates. This strengthens the idea that a robust state-led drive to increase the financial incentives for investment in solar power will be imperative to sustain and further expand the growth of the technology in India.

Shrimali *et al.* (2020) identified the Renewable Purchase Obligation (RPO) mechanism, whereby each state is required to meet a set percentage of its energy demand through renewable sources, as an important driver for the growth of solar in Indian states, with higher RPOs corresponding to greater capacity deployment. An improved focus on solar energy under the RPOs and a more stringent implementation of the policy may catalyze further growth by creating guaranteed demand for solar power and incentivizing more players to enter the sector.

The declining costs of the technology already give solar power an edge over other conventional energy sources, and makes it an increasingly competitive alternative to consider when planning to expand generation in the face of growing power demand. Providing subsidies to protect the technology as it moves through the formative phase, while simultaneously enacting policies (like a carbon tax) that deter the deployment of additional fossil fuel-based energy capacity could help promote solar power further. A renewed focus on addressing the issues with the domestic manufacturing of solar panels identified by Behuria (2020) may further decrease the cost of deployment while simultaneously reducing India's dependence on technology imports and promoting greater energy sovereignty in line with the government's aspirations (Shidore and Busby 2019; Rathore *et al.* 2018)

It is also imperative to make it easier for private investment to flow into the solar power sector and reduce institutional entry barriers. Focused action on improving transparency in the various bureaucratic processes involved in setting up and running a solar power plant including accessing government subsidies, financing, tax-relief, and acquiring permits will help smoothen operations for solar project developers. As noted by Busby and Shidore (2021), it is also important to allow states to experiment with their own solar policies and attract financing from a variety of sources including international development banks and lending institutions.

Though not directly investigated in this thesis, the availability of land has been a major factor limiting the deployment of solar in India. Additionally, the land that does become available for solar projects is often isolated and lacks easy access to the distribution grid (Pargal and Banerjee 2014). Support from the state can definitely help address these issues. Shrimali *et al.* (2020) identified large solar parks as being important drivers of solar power growth in their analysis. Busby and Shidore (2021) have also highlighted the important role played by state-led land procurement in supporting solar power in Karnataka, which ultimately led to it becoming the national leader in solar deployment. Given the complications surrounding land procurement in the Indian context, the ability of the state to ensure availability of land and grid access to solar project developers can be central to attracting greater investment in the sector. However, it is also important to note that given India's still largely agrarian nature and high population density, land is a scarce resource. Additionally, these parks also require large quantities of water, which poses a problem because 80% of India's solar potential is concentrated in areas with high water-stress (Deshmukh *et al.* 2019). In that light, large solar parks cannot be seen as a sustainable, long-term policy for driving the future growth of solar power in India. Turning back to the example of Karnataka, while its growth has indeed been spectacular, it has been short-lived, with rates falling sharply after the Pavagada solar park came online. While solar parks may induce short bursts of rapid growth, there are only so many parks one can build before running out of land. Thus, there is an urgent need to simultaneously explore other, more decentralized formats for solar deployment.

Rooftop solar is one such format which has received special attention from the Indian government. It was supposed to contribute 40% of the 100 GW solar capacity that India planned to deploy under the JN-NSM. However, as of March 2021, the technology has fallen woefully short of its target with installed capacity tallying only 4 GW – a little over 10% of the target. It is important to perform a comprehensive analysis to understand what went wrong, and use the insights thus derived to formulate corrective policies. Given the rapid urbanization India is undergoing, rooftop solar can play a big role in harnessing the country's solar potential to simultaneously tackle the problems of rising energy demands and deteriorating air quality in urban India.

Solar power also faces competition from another low-carbon energy technology – wind power. It predates solar power in the country, and has seen remarkable growth in India over the last couple of decades. Deshmukh *et al.* (2019) have identified a potential to co-locate at least 110 GW of wind and 360 GW of solar PV and suggested that together, they could cover over 35% of India's power demand in 2030. It is essential to harmonize the development of the two technologies through cohesive policy, and ensure that their potential is realized to the fullest.

Lastly, given the central role of the state in deciding the fate of India's solar sector, it is important to retrospect on the performance of the myriad of policies that have been implemented to foster the growth of this technology. It is imperative to understand which interventions work and why in order to eliminate policy paralysis. It is also advisable to ensure a higher degree of cohesion between various policies, and greater communication between different arms of government that interface to influence the solar sector. In light of the highly heterogenous nature of India, it may be optimal to tailor solar energy policies to the social, economic, political, and geophysical contexts of individual states rather than enforcing a top-down policy being commanded by the central government. This is even more relevant given that solar power is at different stages of the technology adoption cycle in different states, and thus has different support mechanism requirements. States where the technology is yet to take off, require more dedicated support to speed the technology through the formative phase. On the other hand, states where the technology has progressed to the growth phase have other requirements pertaining to sustaining growth for an extended period and raising the saturation ceiling closer to the full geophysical potential of the solar resource in that state. It is important that local governments have a say in experimenting with, and adopting policies that are best suited to their individual contexts. This suggestion is in line with the findings of Busby and Shidore (2021) who identified inter-state competition, policy experimentation, and a "solar federalism" as being key to India's solar story so far. Thus, despite growing pressure in the face of target shortfalls, and a larger centralization tendency in Indian politics, allowing "solar federalism" to continue may be crucial to the country's low-carbon transition.

Chapter 6: Conclusions

This final chapter is composed of three sections. Section 1 summarizes the key findings of this research, and is followed by a section briefly outlining a set of recommendations for policy makers. The third section concludes this chapter by highlighting this thesis' limitations and making suggestions for future research.

6.1. Key Findings

The aim of this thesis had been to empirically analyze the growth of solar power in India and assess the feasibility of its solar targets by answering four questions – (i) What are the trajectories and quantitative parameters of the growth of solar power for different states and nationally in India? (ii) Why did some Indian states deploy solar PV earlier than others, and are there significant differences between early and late adopters? (iii) Given the existing trends and patterns of growth, can India and its states be expected to meet the 2022 and 2030 targets? (iv) What can be done to accelerate the deployment of solar power in India?

To that end, this thesis first identifies those Indian states where solar power has achieved takeoff, fits growth models to empirical solar power generation data, and estimates individual quantitative growth parameters for these states. It finds that solar power has taken off in 11 Indian states that together account for about 70% of India's total power generation, most of which are in the solar resource-rich western and southern regions. The estimated national maximum annual growth rate ranged between 0.77-0.87% depending on the growth model. This was higher than the median rate for other countries with mature solar deployment. Sub-nationally, there was a large variation between states, with maximum growth rates varying from 0.4% in Uttar Pradesh to almost 12% in Karnataka. The 11 post-takeoff states were classified into three growth phases – accelerating, stable, and stalling – based on their respective growth characteristics. Just three of these states – Gujarat, Rajasthan, and Chhattisgarh – were still in the accelerating phase, with the other eight evenly split between the stable and stalling growth phases. In light of these findings, this thesis argues that the slowing trend observed nationally can be attributed to this slowing of growth at the state-level.

The second question is answered by performing linear regression and correlation analyses to determine which factors influence the differences in growth characteristics between states. This thesis finds that the incidence of solar takeoff in states correlates with higher global horizontal irradiance (GHI), more expensive coal transport, and higher Ease of Doing Business (EDB) scores, while the takeoff timing is influenced by the state's total solar power generation potential. The factors analyzed included the state GDP, the change in power demand, the total state electricity generation, EDB score, total state solar power generation potential, average state GHI, coal transportation costs, average DISCOM rating, average energy balance, and solar power purchase tariffs. On analyzing the differences between early and late adopters within India, it finds that though later adopters have had statistically shorter transition durations, they do not necessarily achieve higher growth rates during the technology adoption cycle; higher growth rates were linked to higher solar power purchase tariffs but not the takeoff timing.

This thesis approaches the third question by estimating the growth rates that would have been required to meet the national solar targets and compares them to the rates observed for both, solar capacity installation and energy generation. Additionally, the feasibility of achieving the 2022 targets for individual states was also assessed using state-level data. It finds that it is highly unlikely that India will meet its 2022 targets, and posits that it will be extremely difficult to meet the 'soft' targets for 2027 and 2030 unless there are radical departures from observed growth trends for solar deployment in India. Both the capacity installation and energy generation analyses echoed this finding. However, it is worth noting that a large share of the blame for the 2022 target shortfall rests with rooftop solar – while India has managed to install about 36 GW out of the 60 GW utility-scale solar planned under the JN-NSM, only 4 GW out of the 40 GW rooftop solar target had been met as of March 2021. At the state-level, while Karnataka has pre-maturely met its 2022 capacity target, the picture is bleak in a majority of Indian states. Only Rajasthan and potentially Andhra Pradesh can be expected to meet their targets in time.

The fourth question is related to what interventions can help India get back on track to achieve its targets and accelerate solar deployment. This thesis synthesizes results from its analysis of solar power in India with insights from the literature to formulate a set of recommendations that are discussed in detail in the following section.

6.2. Recommendations to policymakers

This thesis argues that India is falling short of fulfilling its solar power potential in general, and its solar capacity installation targets in particular. In order to fulfil its targets, India needs to oversee a massive acceleration in the deployment of solar power across Indian states. This thesis has found that though solar power has taken off in 11 states that account for a majority of the country's power generation, it is no longer accelerating in eight of them. Thus, while it is important to devote attention to inducing takeoff in the remaining Indian states, it may be even more important to catalyze a fresh phase of accelerating growth in states where growth is stable or stalling, as these states together account for about half of India's electricity generation. They are also expected to drive close to 50% of its power demand in 2030. This is a significant challenge given that India's power demand is expected to undergo rapid expansion over the coming decades. In light of the strong role that state policy has played in the growth of India's solar power sector thus far, this thesis makes the following recommendations.

Formulate policy that reflects the immense internal heterogeneity of India. Solar policy in India has largely taken a top-down, command-and-control approach with the central government leading target-setting and policymaking. Given the significant differences in the socio-economic, political, and geophysical contexts of different Indian states, it is imperative to integrate these differences into their respective energy policies and targets. This is especially relevant to solar power as different states are at different stages of the technology adoption cycle, and have different support needs. On one hand, solar power needs extra support and protection in the form of subsidies, tax breaks, and feed-in-tariffs in the states where it is yet to complete the formative phase. Meanwhile, in the post-takeoff states, the focus needs to be on sustaining and/or accelerating growth by enhancing profitability for project developers and attracting greater investment into the sector. It is imperative to improve cohesion between the central and state-level policies, and find a balance that facilitates more localized policy experimentation.

To that end, there is also a need to take stock of the progress thus far and evaluate which interventions have worked and which haven't. Certain policies like the Renewable Purchase Obligations and solar parks have been effective in driving the growth of solar power, while others such as accelerated depreciation and Viability Gap Funding have made less of an impact. Steps must be taken to identify and remove barriers impeding the growth of solar power in the country. Some of these include easing access to land for project development, improving power transmission and distribution systems, and minimizing bureaucratic red-tape and corruption. It is also important to renew focus on domestic R&D and manufacturing of solar energy technologies to reduce India's import burden and enhance its energy sovereignty.

The implementation of rooftop solar PV has largely been a failure, with only 10% of its JN-NSM target being fulfilled as of March 2021. There is an urgent need to revisit what has gone wrong and how the sector can be revived; this is especially important because of the immense potential that the technology has in a rapidly urbanizing India where land is in short supply.

Lastly, it is also important to situate solar power in the bigger picture of India's national energy transition. Solar faces competition from India's primary fuel choice – coal – as well as other low-carbon energy technologies such as wind power. In addition to techno-economic factors, it is also important to look at the social and political aspects of this transition including the antagonisms therein. The fate of India's solar sector is invariably tied to India's push for energy sovereignty, the promise of electricity for all as a public good, the future of coal jobs, the liberalization of domestic coal mining, a newfound push for natural gas, intensifying state-center political conflicts, and a growing demand for cleaner air. This thesis reiterates the need for a comprehensive energy policy that reconciles India's solar aspirations with its bigger social, political, and economic issues and ambitions.

6.3. Broader implications, limitations, and recommendations for future research

The major contributions of this thesis have been to demonstrate that: (i) India is not on track to meet its solar targets, (ii) solar growth is no longer accelerating nationally and in a majority of states where the technology has taken off, (iii) solar power is yet to achieve takeoff in many states, (iv) there are no guarantees that later adopters of solar in India will grow faster to compensate for the delay in takeoff. Additionally, it offers a set of recommendations to help realign India's solar future. On a more general level, this thesis also contributes to the technology diffusion literature by attempting to study how low-carbon energy technologies diffuse within larger electricity systems in the developing world. This sub-national focus is important as it is more localized governance that is ultimately responsible for the implementation of national technology deployment programs. These insights can be used to assess the feasibility of various climate mitigation and energy transition commitments, and inform future policies and targets. This thesis also demonstrates that the speed of technological growth is constrained by counterbalancing mechanisms, and advises caution against making assumptions of limitless, ever-accelerating growth, especially in the context of low-carbon energy technologies in climate change mitigation.

A conceptual limitation of this thesis is that it relies on historical evidence to make estimates about the future. While it adheres to maximum analytical rigor and leverages recognized causal mechanisms of solar power diffusion, departures from the projections made by this thesis due to radically new and unforeseen developments is not out of the realm of possibility. Thus, there is room for more granular analyses that delve deeper into the mechanisms underpinning the growth of the technology at both the national and sub-national scales. This thesis leans towards a more techno-economic perspective in its analysis of the factors influencing solar takeoff and growth, and there is a potential for a more comprehensive analysis through social-technical and political lenses. A comparative analysis of solar policies being implemented by different states could offer fresh insights into regional differences in deployment. This thesis exclusively focused on utility-scale solar and did not analyze rooftop solar PV, which remains an important, though underperforming, component of India's solar mission which deserves closer scrutiny. Following this thesis, similar analyses can also be performed to study the development of wind power and other low-carbon energy technologies in India, as well as in other developing countries in the context of energy sector decarbonization and climate change mitigation.

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Appendix: Data Tables

Appendix Table 1. State-wise explanatory variables for hypothesis testing.

State	GDP per capita, constant prices, 2013 (INR)	Change in power demand over 5 years (w.r.t base year)	TES, 2013 (GWh)	Ease of Doing Business score, 2015	Solar generation potential (TWh)	Avg. GHI (kWh/m²/day)	Coal Transport Cost (INR/kWh)	Average DISCOM score	Average energy balance	Initial Solar power Purchase Tariff (INR/kWh)
AP	39645	7.67%	45527	70.12	520	5.56	1.59	8.1	-1.3	5.25
BR	14356	55.78%	32171	16.41	36	5.05	0.49	7.5	-2	
CT	28087	21.53%	115714	62.45		5.33	0.65	7.5	-0.8	6.44
GJ	59157	21.15%	97199	71.14	1100	5.58	1.67	10	0	4.96
HR	64052	15.12%	25435	40.66	61	5.14	1.62	7	-0.1	5.08
JH	27010	14.21%	26982	63.09	72	5.21	0.3	5	-1.9	5.08
KA	43266	14.56%	49365	48.5	240	5.69	1.16	7.6	-2.6	6.71
MH	65095	17.34%	94700	49.43	1040	5.52	1.01	8.5	-0.5	4.81
MP	24867	41.78%	59647	62	720	5.38	0.86	7	-0.1	5.05
OD	25163	20.13%	46824	52.12	100	5.23	0.28		-0.6	4.81
PB	47854	13.70%	20731	36.73	37	5.01	1.71	8.5	-0.3	5.09
RJ	30839	21.47%	45851	61.04	4200	5.53	1.47	6.4	-0.6	4.34
TS	47100	53.90%	39153	42.45	220	5.53	0.13	8	-1.7	6.45
TN	58360	14.22%	62211	44.58	180	5.76	2.1	6.5	-1	3.47
UT	55375	11.24%	14995	13.36	14	5.01		9.5	-1.4	5.57
UP	18635	13.49%	111843	47.37	260	5.13	1.41	5.7	-7.8	4.81
WB	34177	10.94%	76952	46.9	87	4.96	0.75	7.8	-0.4	

Appendix Table 2. State-wise annual solar and total electricity generation (2013-2021).

State	Annual power generation (GWh)	2013	2014	2015	2016	2017	2018	2019	2020	2021
AP	Solar	108.84	207.11	159.77	282.67	1599.78	3658.97	4965.97	5855.12	7003.9
	Total	87167.25	45526.85	37139.15	58230.59	65248.16	68720.63	63143.82	62943.12	52738.16
AS	Solar	0	0	9.65	31.6	2.69	8.36	6.66	6.15	12.7
	Total	4202.29	4365.22	3708.66	4522.12	5981.37	5972.12	7224.98	8030.37	5969.06
BR	Solar	0	0	0	6.39	109.18	145.34	179.89	160.54	155.22
	Total	14707.45	14939.36	14761.06	20827.01	24514.85	28440.03	32170.52	35360.76	33773

CT	Solar	2.49	11.42	12.65	52.7	120.91	136.54	335.14	326.42	669.54
	Total	68115.77	70930.12	66152.38	89513.29	105686.18	110041.76	115714.3	118229	135199.44
DL	Solar	3.68	3.29	3.18	4.11	5.68	13.41	10.84	136.31	186.58
	Total	10740.93	8637.67	7654.75	6206.1	6253.26	7048.7	7136.04	6015.11	5303.79
GJ	Solar	1145.52	1369.39	1474.56	1497.6	1738.28	2048.4	2410.32	3631.86	4419.7
	Total	90991.22	97198.69	89506.02	104917.26	99748.61	96519.87	96591.35	106949.3	103931.73
HR	Solar	0	0	10.36	114.96	19.7	64.65	72.5	125.14	162.98
	Total	25416.04	26374.22	24843.09	22247.14	18890.44	26605.97	25435.43	17317.01	14879.68
JH	Solar	6.81	0	8.32	19.77	38.47	19.47	19.14	17.48	53.77
	Total	11520.07	14345.18	12239.99	15933.67	14727.43	13997.33	26981.63	26223.04	27176.73
KA	Solar	16.27	38.25	100.39	187.69	524.67	2391.73	7575.83	11221.21	12331.96
	Total	43946.42	49364.51	40730.41	47553.25	43766.67	44668.81	49756.96	45128.91	39483.51
KL	Solar	0	0	0	7.38	26.52	55.35	110.84	143.6	270.19
	Total	6867.66	9249.8	6933.2	6653.34	4130.61	5248.02	7325.09	5466.08	6736.57
MP	Solar	10.82	247.05	562.29	1105.28	1366.1	1911.7	2971.88	3496.26	4283.33
	Total	50695.53	59646.87	62173.96	95740.5	98599.98	111333	121677.7	121100	129553.1
MH	Solar	28.61	257.42	349.32	638.76	577.83	1100.67	2206.62	2372.67	2332.18
	Total	92134.91	94699.94	90430.84	117244.43	118091.71	124308.77	137023.7	131418.2	117576.74
OD	Solar	17.98	34.28	44.94	150.73	210.81	204.77	263.04	362.29	428.94
	Total	41663.62	46212.19	42778.53	57221.8	55841.18	46512.83	46824.37	48253.97	62101.29
PB	Solar	1.29	51.69	129.89	380.57	909.2	1432.07	1492.9	1358.23	1702.62
	Total	21938.16	20731.49	20341.52	23342.89	26492.18	28958.56	30699.66	26025.15	22748.77
RJ	Solar	266.34	1052.23	1259.19	1766.1	2131.61	3469.25	5109.35	7776.56	9975.88
	Total	42365.83	45851.36	45595.9	53947.35	51792.17	51643.61	56978.26	55942.38	54069.15
TN	Solar	25.88	38.87	158.75	507.18	1898.34	2906.01	3554.52	4946.63	5602.45
	Total	53693.92	62210.69	57421.18	76406.83	84581.68	82386.3	83778.51	83498.02	70073.54
TS	Solar		0	138.13	402.51	1337.9	4013.8	6312.28	6263.92	6525.82
	Total		39152.87	33963	36868.2	43391.23	48804.2	49963.03	51854.82	48387.51
UP	Solar	14.11	14.96	20.13	89.75	230.95	637.02	1235.07	1447.05	1707.93
	Total	104346.72	111843.01	94514.38	111329.53	120142.11	128542.28	122772.4	124180.2	126914.52
UT	Solar	0	5.55	11.63	5.87	37.77	291.08	318.29	341.51	336.96
	Total	12438.79	11025.01	10080.06	12765.92	14250.54	15606.6	14995.36	16541.32	14334.95
WB	Solar	0	0	7.58	6.28	14.96	20.47	40.62	64.23	66.78
	Total	46828.64	46069.88	41233.53	46946.62	52192.69	52381.91	76952.06	74311.77	75994.82