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Market Advantage or Policy Effort:

Drivers of Utility-Scale Solar Growth in India

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September, 2025

Vienna

Author's Declaration

I, the undersigned, **Senjuty Bhowmik**, candidate for the PhD degree in Environmental Sciences and Policy declare herewith that the present thesis titled **Market Advantage or Policy Effort: Drivers of Utility-Scale Solar Growth in India** is exclusively my own work, based on my research and only such external information as properly credited in notes and bibliography. I declare that no unidentified and illegitimate use was made of the work of others, and no part of the thesis infringes on any person's or institution's copyright. I also declare that no part of the thesis has been submitted in this form to any other institution of higher education for an academic degree.

Senjuty Bhowmik

Vienna, 22 September 2025

Ideas, results, and figures appearing in this thesis incorporate material from one multi-author working research paper and one multi-author conference paper, both led by the candidate:

[I] Bhowmik, S., Cherp, A., and Vinichenko, V. (pre-print). Technology and policy co-evolution: the case of solar power in India. POLET Working Paper series 2024-4

[II] Bhowmik, S., Jewell, J., Nacke, L., and Cherp, A. Policy Effort to Meet Ratcheted Ambitions: The Case of Utility-Scale Solar in India. 2025. ECPR General Conference. Thessaloniki 26-29 August.

Declaration of generative AI

Generative artificial intelligence (GenAI) was used in this work. I, Senjuty Bhowmik, have reviewed and edited the content as needed and take full responsibility for the content, claims, and references. An overview of the use of GenAI is provided below.

[I] I used **Research Rabbit**, *researchrabbit.ai*, to gather relevant peer-reviewed academic literature and obtain a high-level overview of the existing research landscape.

[II] I used **ChatGPT**, *chatgpt.com*, primarily for text editing purposes. The tool was also used to troubleshoot issues during data analysis and coding.

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Table of Contents

List of Figures

List of Tables

Abbreviations of state names

IN: India

Region: North-west

GU: Gujarat

HA: Haryana

MP: Madhya Pradesh

PU: Punjab

RA: Rajasthan

UT: Uttarakhand

Region: South

AP: Andhra Pradesh

KA: Karnataka

KE: Kerala

MH: Maharashtra

TN: Tamil Nadu

TE: Telangana

Region: North-east

AS: Assam

BI: Bihar

CH: Chhattisgarh

OD: Odisha

UP: Uttar Pradesh

WB: West Bengal

General abbreviations

AR6: IPCC Sixth Assessment Report

AT: Auction Tariff

C&I: Commercial and Industrial consumers

C-parity: Cross-source parity or Parity with coal

CAPEX: Installation cost or Capital Investment cost

CBAM: Carbon Border Adjustment Mechanism

CEA: Central Electricity Authority

CERC: Central Electricity Regulatory Commission

CoC: Cost of Capital

CRF: Capital Recovery Factor

CUF: Capacity Utilisation Factor

D-parity: Developers' parity

DISCOM: Distribution Company/ Power distribution utility

EU: European Union

FiT: Feed in Tariff

FRED: Federal Reserve Bank of St. Louis

GDP: Gross Domestic Product

GOI: Government of India

GW: Gigawatt

ICED: India Climate and Energy Dashboard

IEA: International Energy Agency

INR: Indian Rupee

IPCC: Intergovernmental Panel on Climate Change

IREDA: Indian Renewable Energy Development Agency

IRENA: International Renewable Energy Agency

ISA: International Solar Alliance

ISTS: Inter-state Transmission Scheme

JNNSM or NSM: Jawaharlal Nehru National Solar Mission

KUSUM: Agriculture-focused scheme (*Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan Yojana*)

KW: Kilowatt

KWh: Kilowatt-hour

LCOE: Levelised Cost of Electricity

LCOECal: Calculated Levelised Cost of Electricity

LCOEIrena: Levelised Cost of Electricity as published by IRENA

LCR: Local Content Requirement

MNRE: Ministry of New and Renewable Energy

MOP: Ministry of Power

MVA: Moving average

MW: Megawatt

NCL: Northern Coalfields Limited

NTPC: National Thermal Power Corporation

NZE: IEA Net-Zero Emissions Scenario

OECD: Organisation for Economic Co-operation and Development

OPEX: Operation and Maintenance Cost

PPA: Power Purchase Agreement

PPC: Power Purchase Cost of distribution companies

PV: Photovoltaic

R&D: Research and development

R3: Three-year moving average growth rate

R5: Five-year moving average growth rate

RBI: Reserve Bank of India

RE: Renewable Energy

REC: Renewable Energy Certificate

RPO: Renewable Purchase Obligation

S-parity: Cost parity

Scenario LastR3: Scenario based on the last three-year moving average growth rate

Scenario MaxR3: Scenario based on the maximum three-year moving average growth rate

Scenario TargetR3: Scenario where capacity targets are met.

SECI: Solar Energy Corporation of India Limited

SERC: State Electricity Regulatory Commission

TWh: Terawatt-hour

U-parity: Price parity

UDAY: Financial recovery package for state distribution companies (*Ujwal DISCOM Assurance Yojana*)

US: United States

USD: United States dollar

VALCOE: Value Adjusted Levelised Cost of Electricity

WEP: Wholesale Electricity Price

WTO: World Trade Organisation

Acknowledgements

"When I meet you, in that moment, I'm no longer a part of your future. I start quickly becoming part of your past. But in that instant, I get to share your present. And you, you get to share mine. And that is the greatest present of all." — Sarah Kay, Hiroshima.

In the grand scheme of things, life is but a fleeting moment. Within that moment, we get to explore the joy of learning, perhaps contribute to that vast body of knowledge, and, if fortunate, help turn insight into action that benefits society. What makes going after this extraordinary endeavour possible is always, always the people, who are generous with their time, kindness, and wisdom. This dissertation exists because of those who shared their present with me, shaping not only the work but also the person behind it.

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I dedicate this dissertation to my late grandparents — *Thammi, Dadu, Dida, and Bomma* — for nurturing my dreams.

Abstract

Accelerating the low-carbon energy transition requires rapid deployment of renewable energy (RE) technologies, especially in developing countries like India. A key question is – how much of this acceleration can be left to technology cost decline, and how much must be actively steered by policymakers? On this, the literature remains divided, with disagreements along temporal and spatial dimensions.

Over time, some argue that falling costs reduce the need for policies as market forces take over. Others emphasise that technology growth continually reveals new barriers that demand sustained policy support. Across space, they argue that developing countries can benefit from technology learning and transfer from pioneering countries. Others emphasise that higher investment risk in developing countries impedes transfer, requiring active policy engagement.

To arbitrate between the two sides, I examine the case of utility-scale solar in India, across both temporal (2004–2024) and spatial (18 states) dimensions. This is because understanding the relative role of cost decline and policies in shaping future RE growth, in developing countries, requires examining their relative role in past accelerations. Since 2014, utility-scale solar in India has been undergoing such acceleration.

To investigate, I develop a four-step semi-quantitative approach that integrates the techno-economic, political, and socio-technical perspectives on energy transitions. I track cost trends using cost and price parity specific to regions. I measure policy effort by tracing the evolution of policy ambitions, and through the density and diversity of policy measures, using an original classification scheme. Then I map how costs and policies co-evolve with technology growth, shaped by the changing capacities and motivations of two main actors — public off-takers, who contract solar electricity, and private developers, who install solar power projects. I establish causal links through process tracing. Throughout, I account for federal and state-level differences.

I find that, despite significant cost decline and the country's strong market advantage, utility-scale solar in India has been and continues to be policy-driven. As solar deployment grew, more numerous and diverse policies became necessary to address evolving barriers. I systematically show what these barriers are at different levels of deployment. Compared with technology-pioneering countries, system integration and grid expansion policies emerged earlier, whereas domestic manufacturing policies appeared later, underscoring that developing countries cannot simply leapfrog on technological progress alone.

Tracing technology-cost-policy feedbacks revealed that while policies consistently enabled growth, they also sometimes constrained it. Growth slowed due to backlash not from incumbent industries but from within the niche industry itself, when industry groups did not gain equally from accelerated deployment. Throughout, while declining cost did not displace the need for policy support, it created space for tougher and more ambitious policymaking. Finally, despite strong policy involvement, solar growth sub-nationally remained highly uneven, with no evidence of convergence between early and late adopting regions. In fact, technology-cost-policy feedback reinforced spatial divergence, raising questions on the compatibility of RE acceleration with equitable development.

For policymakers and other energy policy scholars, this dissertation offers an in-depth insight into the policy effort required to accelerate renewables in a developing country context.

Keywords: energy policy, accelerating renewables, solar PV, India

1. Introduction

1.1 RE acceleration is paramount, yet challenging.

The science is unequivocal that mitigating climate change demands a fundamental transformation in how we produce and consume energy (IPCC 2023). Two leading authorities on climate and energy — the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) — have outlined multiple viable pathways to limit global warming to 1.5°C by 2100, and achieve net-zero emissions by 2050, respectively (IEA 2021b; IPCC 2023). Both agree on three main points. First, the electricity sector is at the heart of the transition. Not only must current ways of generating electricity be decarbonised, but the sector must also expand to accommodate those that are not currently electrified – such as transport, industry, and residence – using clean energy. According to the IEA's Net Zero Emissions (NZE) scenario, the share of electricity in final energy consumption must rise from 23% today to nearly 50% by 2050 (IEA 2021b, 2025). Similarly, the IPCC's Sixth Assessment Report (AR6) projects electricity must account for 34–71% of final energy use by 2050 to limit warming within 1.5°C (IPCC 2023).

Second, to meet this growing electricity demand, rapid and sustained deployment of renewable energy (RE) technologies, like solar PV, is needed. From a current 15% share of global electricity supply, the IEA's NZE scenario estimates solar and wind will need to supply around 70% of electricity by 2050 (IEA 2021b, 2025). The IPCC AR6 similarly projects that renewables must contribute 59–97% of electricity generation by mid-century, with solar alone providing 27–40% (IPCC 2023). Finally, much of the deployment of new RE must occur in the emerging economies of the Global South. Here, fossil fuels currently account for 60–80% of total electricity generation, and energy demand is rapidly rising (IEA 2025). In 2024 alone, these countries accounted for over 80% of the total rise in global energy demand (IEA 2025). Without transitioning to low-carbon energy sources, there is a risk of countries getting locked into carbon-intensive development pathways (IPCC 2023).

The challenge, however, lies in navigating the complex interplay between the unevenness of global capacity, the urgency of the needed transformation and the insufficiency of current progress, and the sheer scale of integrating a large share of renewables in electricity generation.

Challenge 1: The unevenness of global capacity

Emerging economies enjoy a significant market advantage. They have abundant renewable energy resources (particularly solar) (IPCC 2023), a growing electricity market (IEA 2025), and the option to adopt advanced technologies from pioneering countries, thereby leapfrog carbon-intensive development pathways (Goldemberg et al. 1987). Yet, these advantages coexist with a set of structural challenges within the broader society and in the electricity sector itself. In many countries, the sector originally evolved under external influence (Williams and Ghanadan 2006), the legacy of which has led to knowledge gaps and governance inefficiencies (Acemoglu et al. 2001), exacerbated by successive complex political economy developments (Dubash et al. 2018; Ordonez et al. 2023). Sector reforms have not fully addressed these inefficiencies, and in many cases, the process remains incomplete (Joskow 2008; Urpelainen and Yang 2019). As a result, the power sector performance has suffered, visible through rigid power markets, grid unreliability, low cost recovery, and financially constrained power utilities (Cantarero 2020; Dubash et al. 2018; Huenteler et al. 2017).

Outside the power sector, governance challenges persist. Limited public trust coupled with the prevalence of a strong informal economic sector, constrains public revenue and limits the state's capacity to deliver basic public services, (Hansen et al. 2018) like electricity. Plus, land conversion and usage remain highly contested due to unclear property rights, competing land-use demands, culturally embedded ownership norms, and a long history of political resistance along socio-economic lines (Meyfroidt et al. 2022; Wehrmann 2008). Most importantly, access to finance remains constrained. High cost of capital, perceived policy and currency risks, and underdeveloped domestic markets contribute to an elevated risk of investments, impeding countries' ability to adequately absorb global climate finance (Ameli et al. 2021; Egli et al. 2023; Steffen 2020).

Challenge 2: The required pace of transition and insufficiency of current progress

Energy transitions are inherently complex, multi-dimensional, non-linear, and non-deterministic processes involving dynamic changes in actors, networks, and institutions (Sovacool and Geels 2016). As a result, historically, these transitions have unfolded slowly, often taking decades and centuries to unfold (Fouquet and Pearson 2012; Grubler et al. 2016; Smil 2016). Past transitions were driven by a combination of technological innovation (Grubler et al. 2016; Smil 2018), population growth and economic development (Kander et al. 2014; Perez 2002), and geopolitical imperatives to diversify sources and enhance energy security (Cherp and Jewell 2011; Yergin 2006).

However, the current low-carbon energy transition is unique in its urgency and normative direction. Unlike in the past, the RE transition is actively shaped by a common goal to solve a global problem (Sovacool and Geels 2016). It is also guided by a rush to reach science-backed climate targets (Rogelj et al. 2018). Accelerating RE deployment to limit global warming to 1.5°C by 2100, or reach net-zero emissions by 2050, requires a much faster pace than historically precedented (Cherp et al. 2021; Suzuki et al. 2023; Vinichenko et al. 2023). Particularly, from solar photovoltaic (PV) (IEA 2025; IPCC 2023). The good news is that decades of sustained policy support have significantly lowered the cost of solar electricity production (IRENA 2024a; Nemet 2019). In response, globally, solar growth has accelerated (IEA 2023b; IRENA 2024a; Nemet 2019). Many anticipate that this pace will continue or even be exceeded in the future (Nijsse et al. 2023; Victoria et al. 2021; Way et al. 2022). Yet, others are more cautious. They observe that current deployment rates are not yet aligned with the levels required to meet climate targets (Jakhmola et al. 2025; Suzuki et al. 2023; Vinichenko et al. 2023). Plus, planned energy scenarios fall short of what is needed to limit global warming to 1.5°C (IRENA 2024b).

Challenge 3: The incompatibility of renewables with existing electricity systems

The final challenge lies in the sheer scale of integrating a large share of renewables into existing electricity systems, which were built around operationally and qualitatively different types of energy technologies. For example, RE systems are typically **decentralised**, unlike the relatively centralised and vertically integrated models of the past (Blazquez et al. 2020; Christophers 2024). Plus, installations are owned and operated by millions of small, often private developers, doing business with traditional public-owned utilities (Alova 2020; IEA 2017; Steffen et al. 2018). These differing **ownership** structures introduce coordination challenges among enterprises operating under separate interests and capacities (Steffen et al. 2022).

In cases where RE generation is large-scale and centralised, it typically requires more **land** per unit of energy produced (Blazquez et al. 2020; Christophers 2024). Many suggest that global land availability is sufficient for the required RE uptake (Denholm et al. 2022; Nonhebel 2005; Perpina et al. 2024). Others, however, emphasise that mere availability does not equate to accessibility (Ven et al. 2021), citing barriers on competing land use, ownership, and conversion (Scheidel and Sorman 2012). Furthermore, land availability somewhere does not guarantee electricity everywhere. High-potential generation sites remain located far from demand centres, requiring an expansion of **transmission** infrastructure (Christophers 2024). Another driver for transmission upgrades is the variable and intermittent nature of RE electricity production. This bears implications for electricity pricing, new project investments, grid stability, and reliability of electricity supply (Hirth 2013; IEA 2024a; Markard 2018; Martinot 2016).

Concurrently, the **financing** structure of RE technologies remains unique. Upfront costs are high while operating costs are low (Egli et al. 2023; Steffen 2020), making project viability highly dependent on access to finance at the start (Steffen 2020) and stable, long-term revenue streams in the (approximately) 25 years of operation. Neither is simultaneously known and guaranteed (Hirth 2013; Peña et al. 2022; Prol et al. 2020). Finally, RE transition remains profoundly a matter of **politics** (Köhler et al. 2019). At the national level, it involves navigating contestations around land, inclusion of new types of actors, shifting interests within and beyond the electricity sector, and evolving power relations between existing and new industrial groups (Ayoub and Geels 2024; Breetz et al. 2018; Geels and Schot 2007). Internationally, increasing grid interconnection across borders (Fang et al. 2024), and the global competition for raw materials (Lowe and Drummond 2022; Lundaev et al. 2023; Rabe et al. 2017) introduce geopolitical and supply chain considerations. In other words, politics holds potential to generate both support for and resistance to RE uptake (Meckling et al. 2017; Pahle et al. 2018; Patterson 2023; Sewerin et al. 2023).

1.2 What will drive acceleration — market advantage or policy effort?

Given the required scale and pace of accelerating RE technologies, it is important to understand what policymakers in developing countries must do. There is a broad consensus that, based on Wright's Law (Wright 1936), the growth of RE technologies will be enabled by the speed of technological learning (Grubler et al. 2016; Nijsse et al. 2023; Rubin et al. 2015). It is equally acknowledged that growth will be contingent on contexts and therefore, deeply shaped by socio-technical and political factors (Köhler et al. 2019; Sovacool and Geels 2016). In other words, RE uptake hinges on: (i) technology cost decline; and (ii) the policy(maker's) effort to navigate complex, context-specific challenges. The literature, however, remains divided on the relative role of each of these enablers in accelerating RE growth. One side argues that once technology costs fall, market forces can take over with less policy support needed. Another side contends that sustained policy support is essential even after costs decline. In other words, the market-driven view emphasises the centrality of technology learning, while the policy-driven view foregrounds contextual attributes. The disagreement rests along both temporal and spatial dimensions.

Temporally, the market-driven view accepts that early policy support is necessary to reduce technology costs but expects markets to take over once costs decline and the technology becomes competitive (Creutzig et al. 2017; Liñeiro and Müsgens 2025; Nijsse et al. 2023; Victoria et al. 2021). The policy-driven view counters that growing cost competitiveness alone does not eliminate barriers, such as grid integration (Markard 2018; Ollier et al. 2024), land acquisition (Frantál et al. 2023; Scheidel and Sorman 2012), and resistance from incumbents (Breetz et al. 2018; Geels 2014), imminent in later stages of RE integration. As a result, sustained policy support remains necessary.

Spatially, the debate concerns the relative role of cost decline and policies in a technology-recipient, typically developing country. The market-driven view suggests that recipients can benefit from the experiences of technology-pioneers (typically developed countries), and easily adopt advanced technologies, with comparatively less policy support (Arndt et al. 2019; Bogdanov et al. 2021; Goldemberg et al. 1987; Gulagi et al. 2022). In contrast, the policy-driven view contends that challenges that impeded early adoption often persist and inhibit eventual uptake in recipients (Comin and Hobijn 2010a), demanding greater and more sustained public sector engagement in these contexts (Ameli et al. 2021; Gallagher 2006; Yap et al. 2022).

As I discuss further in Chapter 2, together, the debates reveal an ongoing disciplinary disconnect. On one side are those who prioritise macro-level, generalisable, quantitative insights common for modelling climate pathways based on techno-economic cost optimisation. On the other side are those who argue energy transitions are embedded in socio-political contexts and cannot be fully captured through techno-economic modelling alone. See (Anderson and Jewell 2019; Beek et al. 2020; Geels et al. 2016; Jewell and Cherp 2023; Trutnevyte et al. 2019). The latter group proposes alternative frameworks that foreground institutional, political, and social dynamics (Cherp et al. 2018; Geels 2011; Trutnevyte et al. 2019). Yet, they fail to offer operational insights on energy and climate solutions, or practical ways to improve realism in energy models (Hirt et al. 2020). Furthermore, the majority of empirical work here, both qualitative and quantitative, focuses on developed countries (Rogge and Johnstone 2017), while much of the future RE deployment must take place in developing regions. In other words, while the relative role of costs and policies to accelerate RE technologies remains debatable overall, there is further incomplete understanding of the role of these factors in developing contexts.

1.3 Research questions, objectives and analytical approach

To arbitrate between the two sides and meaningfully extract policy insights, I address four research questions in this dissertation. The first two relate to the temporal dimension of the debate, while the last two relate to the spatial dimension.

1. What is the relative role of markets and policies in accelerating RE technology growth over time?
2. How do policies change over time with increasing RE deployment?
3. What is the relative role of policies in driving RE technology growth in a technology-recipient country?
4. How do policies change across space with increasing RE deployment? Do they enable late adopters to catch up?

To answer, I develop an analytical framework in Chapter 3 that incorporates insights from both the market-driven and policy-driven viewpoints. The novelty of the framework is that it provides a holistic and moderately generalisable approach that can be calibrated to apply to broadly similar technological and country contexts.

The framework follows a four-step semi-quantitative methodology. First, I assess cost competitiveness using cost and price parity specific to individual sub-national provinces. Second, I measure policy effort by creating a database of policy ambitions over time (both national and sub-national), and capturing the type and density of over 500 policy measures through an original classification scheme. Third, I analyse how costs and policies co-evolve with technological growth over time and space, shaped by key actors involved. This includes an examination of 296 successful auctions, representing 165 GW of contracted capacity across 51 procurers and over 95 developers. It also involves an analysis of market concentration across major market players. Finally, I establish causal links using process tracing by combining time-series visualisations with counterfactual reasoning.

1.4 Why utility-scale solar in India?

To understand the relative role of costs and policies in accelerating RE growth in developing countries, in the future, it is important to look at what has happened in the past. I answer the research questions, using the case of utility-scale solar in India — one of the countries where an urgent RE transition is most needed (IPCC 2023). This is for four main reasons.

First, India is a developing, technology-recipient country, which benefits from global innovation and a strong domestic market advantage. The country has abundant solar resources (Deshmukh et al. 2019; MNRE 2025c), and rising electricity demand (IEA 2025). Global technology learning and early-stage domestic policies have brought down the cost of solar electricity production, significantly (IRENA 2024a). Thus, it is a perfect case where market forces are strong and can take over. **Second**, policymakers in India have demonstrated consistently increasing commitment towards solar PV. A target to achieve 20 GW by 2022 was set in 2010 (GOI 2010). This was later raised in 2015 to 100 GW by 2022 (MNRE 2015b). In 2021, a new target was set to achieve 500 GW of total RE capacity by 2030 (McGrath 2021), with 300 GW from solar PV (CEA 2023).

Third, during this time, utility-scale solar has witnessed remarkable growth. From 0 GW in 2010, installations reached 7 GW in 2015, 52 GW in 2022, and 90 GW as of August 2025, accounting for 78% of the country's total solar capacity. So, the question is — did technology growth and target revision follow natural market-led logics, or did target revision actually demonstrate increased policy ambition, and achieving it required concerted policy effort? **Finally**, India's federal structure allows comparative analysis: (i) to assess the generalisability of claims across regional contexts; and (ii) to better understand policy effort across national and sub-national governance levels.

Aligning with this case selection, I address the third and fourth research questions on the spatial dimensions of technology growth, at the national and sub-national level, respectively.

1.5 Structure of the dissertation

I have structured this dissertation in eight chapters separated across three sections. See Figure 1.1. Following this introduction, Chapter 2 reviews the market and policy-driven positions across time and space, and summarises the knowledge gap that culminated in the four research questions. Chapter 3 outlines the conceptual and analytical approach used to answer the research questions. Chapters 4, 5, and 6 present the empirical analysis: Chapter 4 examines the temporal and spatial patterns of solar growth; Chapter 5 focuses on changing solar cost-competitiveness and growth across time and space; Chapter 6 explores the co-evolution of policy effort and solar growth across time and space. Chapter 7 synthesises the main contributions of this dissertation and discusses the limitations and potential directions for future research. Finally, Chapter 8 provides a high-level summary directed towards policy relevance.

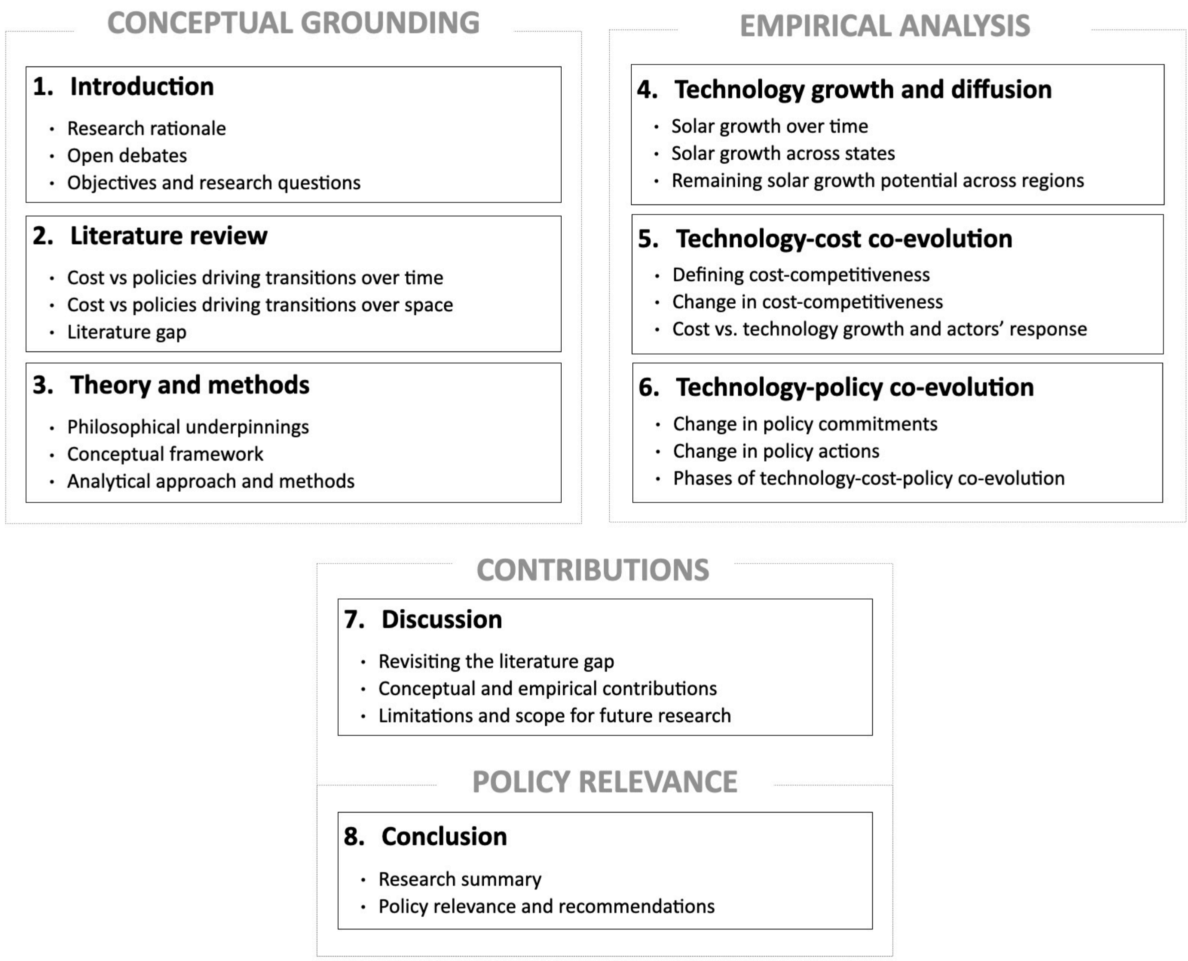

Figure 1.1: Structure of the dissertation

2. Literature Review

The debates on the relative role of cost decline and policies in accelerating RE growth over time and space reveal an ongoing disciplinary disconnect. Here, I synthesise the origins and key arguments of the two positions. The Chapter is divided into four main sections: the first two on temporal dimensions, the remaining two on spatial dimensions. Section 2.1 contrasts market- and policy-driven views of RE growth over time. Section 2.2 examines technology-policy co-evolution. Section 2.3 analyses dominant narratives in RE transitions in developing countries. Section 2.4 explores how transitions unfold between early and late-adopting regions. In Section 2.5, I summarise the key knowledge gaps and align them with the four research questions.

2.1 Markets vs Policies driving RE transitions

The IEA (2023a) defines market-driven RE expansion as growth through market mechanisms, such as bilateral power purchase agreements (PPAs), corporate sales, and certificate schemes. Policy-driven growth, on the other hand, results from instruments like feed-in tariffs, auctions, or regulated utility projects. In this dissertation, I adopt a similar yet slightly broader definition. I define market-driven RE growth as that which necessitates less new policy adoption, and policy-driven as one that requires increasingly more policies.

2.1.1 The market-driven argument

The market-driven view broadly includes those who argue that techno-economic factors are paramount for successful energy transitions. A frequently cited example is Fouquet's observation of 19th-century UK, where kerosene couldn't compete with cheaper city gas, and only when electric lighting became far cheaper did it replace gas (Fouquet 2016).

This focus on economic viability carries over in discussions about RE growth. Technologies like solar and wind have been around for decades. Yet, they started gaining attention in the 1970s after the oil crisis (Howard 1980; Smil 2018). Two decades later, in the 1990s, when global climate concerns magnified, these technologies were still too expensive (Salpukas 1995). See Figure 2.1. They simply weren't profitable, i.e., the costs of producing electricity from solar and wind were higher than market electricity prices. In other words, electricity could be generated at much cheaper costs from existing fossil fuel sources. Environmental economists argued that renewables appear expensive because the environmental costs of fossil fuel generation were not factored into their market price (Owen 2006; Stern 2007). Thus, for market forces to drive RE growth, policies should address these market failures by enabling correct price signals (e.g., by putting a price on carbon) (Jaffe et al. 2005; Stern 2007). Another complementary strategy would be to lower RE costs by accelerating technology deployment, so that increased learning through Wright's Law of doubling of production (Wright 1936), would enable economies of scale and speed up cost decline (Jaffe et al. 2005). Gillingham and Sweeney (2010) listed twenty such market failures that policies must address to efficiently speed up RE deployment. In other words, the main role of policymakers, under this view, is to correct market failures and arrive at a configuration where the (invisible hand of the) market can take over.

'Cost' has long been used as a proxy of the 'right' market configuration (Christophers (2024), p. 99-131). This emphasis is evident in the regular tracking of RE Levelised Cost of Electricity

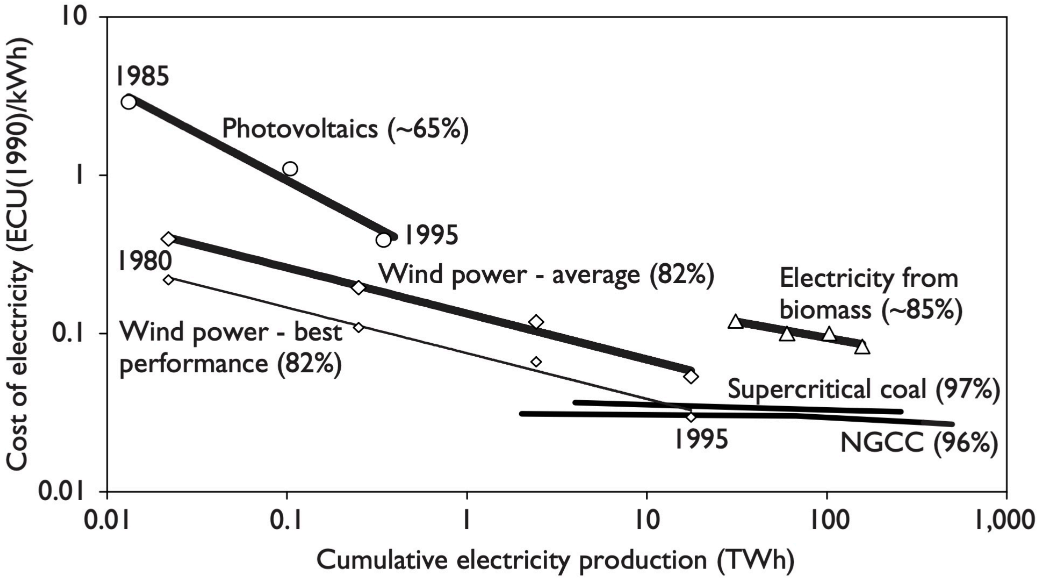

Figure 2.1: Cost of electricity production from different energy sources in the European Union between 1980-1995.
Source: IEA (2000), p.21

(LCOE), across major science and policy works (IEA 2021a; IPCC 2023; ISE 2025; Lazard 2025). LCOE is understood as the absolute cost of producing one unit of electricity for the lifetime of a RE project (Timilsina 2020). Another way of interpreting cost has been in relative terms, or by calculating grid parity (Munoz et al. 2014). For example, in 2011, the IEA's World Energy Outlook (p. 178) noted: "The change in the mix of technologies and fuels used to produce electricity is driven mainly by their relative costs, which are influenced by government policies" (IEA 2011). Relative cost is where the LCOE of a RE technology is compared to the LCOE of other energy sources or against different electricity market prices[1]. The rationale of calculating absolute or relative cost is to anticipate how much policy support would be needed based on it. This forms the basis of energy model construction, like the Integrated Assessment Models, that have gained popularity at the science-policy interface (Anderson and Jewell 2019; Beek et al. 2020).

From here, the core market-driven argument is that cost decline signals the achievement of an optimal market configuration. Once this point is reached, little to no government support is re-

[1] I discuss relative cost and grid parity in detail in Section 3.2.2

quired, as the self-sustaining attributes of the technologies are unlocked (Creutzig et al. 2023; Victoria et al. 2021). Even when some policy support remains necessary, it requires less public spending, as renewable investments become profitable simply through higher market revenues (Liñeiro and Müsgens 2025). As a result, decarbonisation via renewables is framed as the most cost-optimal pathway for governments (Way et al. 2021). Figure 2.2 shows the more recent evolution of the costs of generating electricity from key RE sources, and these are often shown with sharply accelerating growth in said technologies (See Figure A.1).

However, many have questioned how well cost and traditional metrics of calculating costs capture the on-ground realities of RE uptake (Christophers 2024; Sovacool and Geels 2016). Even those emphasizing the strength of techno-economic factors recognise that markets alone are not enough. For instance, Grubler et al. (2016) argues that market forces need to be actively supported by policies such as public R&D funding and demand-side measures. Fouquet (2016) highlights political action and consumer preferences as important influences. Meanwhile, Smil (2016) cautions against relying too heavily on either markets or policies, noting that transitions have historically been slow regardless of interventions. In terms of better operationalisation of costs, some have proposed improvements or alternative metrics[2]. For example, Jenner et al. (2013) and Christophers (2024) proposed profitability-based indicators. Choi et al. (2015), Lund (2015), IEA (2024b), and (Wang et al. 2025) proposed different ways to calculate LCOE and/or grid parity. For example, the IEA (2024b) introduced VALCOE (Value-Adjusted LCOE) to account for the cost of variability and intermittency in RE electricity. In short, while cost remains central to the market-driven debate, measuring and interpreting that cost is far from universally agreed upon.

[2] I name a very few here. The list is very long.

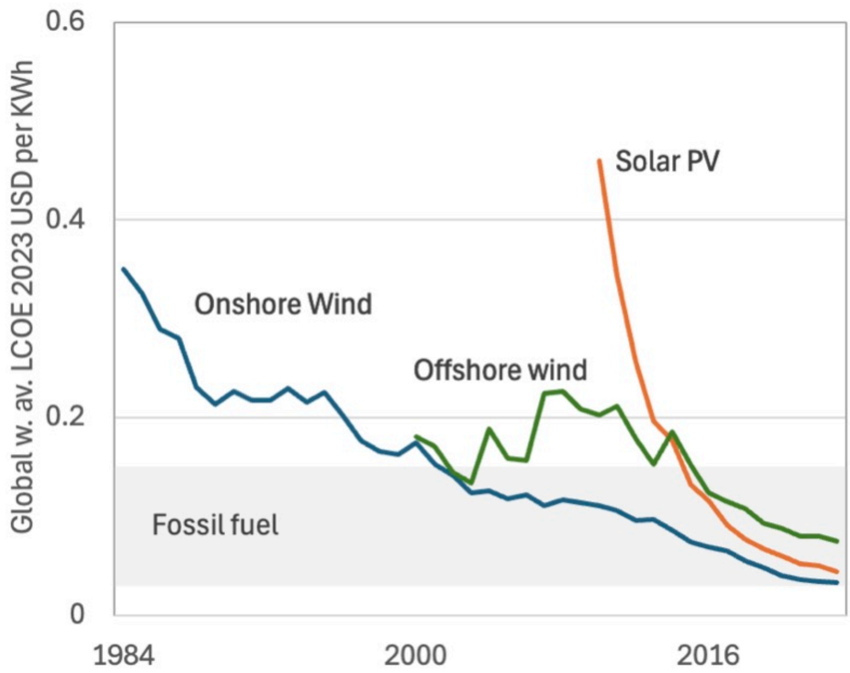

Figure 2.2: Global weighted average LCOE from RE and fossil fuel sources between 1984-2023.
Source: Own illustration. RE LCOE data is based on IRENA (2024a) database. The band for fossil fuel costs is extrapolated from IPCC (2023) p.54.

2.1.2 The policy-driven argument

For this view, four main arguments are often put forward. **First**, politics can override economics. For example, Kern and Rogge (2018) argue that political entrepreneurs, advocacy coalitions, or major crises can shape transition trajectories independent of cost considerations (see also Kingdon (1985) and Geels and Penna (2015)). Based on this, they suggest that low-carbon transitions can occur rapidly — not necessarily due to improved cost competitiveness, as market proponents might argue, but because of shifts in political and public interest[3]. One example is that the transition from coal to gas in Germany and the UK in the 1980s, was driven not by price signals or environmental concerns, but by political objectives — reunification in Germany and market liberalisation in the UK (Atalla et al. 2017). From this emerges a **second** point — that historical evidence suggests that energy transitions have almost always been politically driven (Aklin and Urpelainen 2013; Suzuki 2024). Therefore, the policy-driven

[3]see also Sovacool (2016)

argument is not a break from the past, but in fact, how energy transitions have historically unfolded.

Third, while proponents of both the market- and policy-driven views agree that the early stages of RE technology growth[4] must be actively supported by policymakers, the perspectives depart from each other on the role of policies after (technology) cost declines. The policy-driven view rejects the market failure approach to policy action (Grubb et al. 2015; Mazzucato 2016; Negro et al. 2012; Woolthuis et al. 2005). They argue that given that RE technologies are fundamentally incompatible with electricity systems of the past (Blazquez et al. 2020; Christophers 2024), policies must take a ”system failure” approach and forge a “grand transformation”(Mazzucato 2017; Mazzucato and Semieniuk 2018). Policymakers’ role, therefore, would be to actively shape innovation, coordinate structural shifts, break path dependencies, and support “key processes” or “functions” (Bergek et al. 2008). Over time, even the IEA has revised its earlier cost-optimistic views. For example, in 2014, it acknowledged that despite achieving grid parity, onshore wind still required subsidies and long-term policy frameworks to remain competitive (IEA 2014).[5]

Finally, at its core, the policy-driven view challenges the over-reliance on costs as the primary basis for determining policy needs. The main point being that while LCOE captures technology improvements, it ignores broader socio-technical and political constraints (Sovacool and Geels 2016), such as land access (Susskind et al. 2022), compensation for fossil fuel phase-outs (Breetz et al. 2018; Nacke et al. 2024), and grid integration costs (Ayoub and Geels 2024; Markard et al. 2020; Ollier et al. 2024; Wang et al. 2023). All of these are borne by different actors at different points in time and vary across geographical contexts. For example, Christophers (2024) (p. 133 - 164) notes that while RE developers may benefit from policies like feed-in tariffs and purchase obligations, utilities could face losses from stranded assets in the early phases of growth. Eventually, falling technology costs may push developers to sell

[4] Or when technology costs are high.
[5] Also in Choi et al. (2015)).

generation at lower prices that minimise their profit margins, while power utilities benefit from lower procurement prices. These asymmetries may also extend across supply chains — coordinated development between technology and industry policies, such as in wind manufacturing in Europe or solar in China, fostered homogenous cost development across industry actors (Nemet 2019). In contrast, misaligned progress for solar PV in India raised costs for project developers at higher growth stages (Behuria 2020).

These criticisms reflect a broader view in transition studies that sees energy transitions not as linear, purely techno-economic processes, but as complex socio-technical and political shifts shaped by dynamic interactions between actors, networks, and institutions (Geels 2002). Yet, while this literature raises valid concerns about how costs are measured, or how the real costs of RE installations remain unknown, most empirical work remains case-bound, qualitative, and limited in their ability to quantify socio-technical and political costs of RE acceleration, and the adjacent policy support required (Hirt et al. 2020). Some scholars have begun to address this gap. Theoretically, Cherp et al. (2018) call for integrating socio-technical, political, and techno-economic perspectives. Empirically, Wang et al. (2023) estimate grid integration costs for renewables in China; Nacke et al. (2024) assess coal phase-out compensation schemes. Bi et al. (2023) examine political costs through sectoral and regional trade-offs. Kazlou et al. (2024) analyse investment risks due to project failures in CCS. Yet, most focus on individual policy instruments rather than the full policy portfolio that co-evolves with a technology.

2.2 Technology-policy co-evolution

The market- and policy-driven views diverged on the timing and intensity of policy support necessary for RE technology growth. I now turn to literature that explores the complex and dynamic co-evolution between technological growth and policy change. Scholars here, rather than viewing policy as an external driver of technological growth or enabler of market behaviour, emphasise a reciprocal relationship in which technological growth influences policy design, while policy choices, in turn, shape the direction and pace of technological growth. In other words, this stream moves beyond the binary of market versus policy as drivers of technology growth, recognising instead that they mutually reinforce each other. The review is divided into two parts. The first subsection maps the conceptual fundamentals of technology-policy co-evolution over time. The second examines how these dynamics are empirically explored.

2.2.1 Multiple origins of feedback in technology-policy co-evolution

The literature on technology-policy co-evolution has emerged with contributions from innovation studies, political science, and environmental economics (Edmondson et al. 2019; Kern et al. 2019; Lehmann 2010; Reichardt and Rogge 2016; Schmidt and Sewerin 2017). Two key theoretical foundations are *policy feedback theory* (Pierson 1993), bridging political science and environmental economics, which examines the nexus between policy feedback and political change; alongside the emerging *technology feedback theory* (Schmidt and Sewerin 2017), bridging political science and innovation studies, which focuses on the interplay between policy, technology, and politics (Figure 2.3). Both conceptualisations emphasise recursive, path-dependent processes. Broadly, four main origins of feedback emerge — political, technological, policy, and external/contextual. Each evolves and influences not only itself but also the others, generating reinforcing (positive) or undermining (negative) effects on the trajectory of technology growth and policy change.

As Meadowcroft (2011) puts it, "behind policy there is always politics". **Politics** is central in shaping feedback, with policymakers playing an integral role. Policymaking unfolds under conditions of uncertainty (Lindblom 1959), limited foresight (Hoppmann et al. 2014), institutional and resource constraints (Lipsmeyer et al. 2017), and multiple, complementary, and/or contending priorities (Ollier et al. 2020), all of which dynamically evolve. Lindblom (1959) famously described the policy-making process as "muddling through"— an incremental, trial-and-error approach to decision-making in response to immediate challenges, often without fully

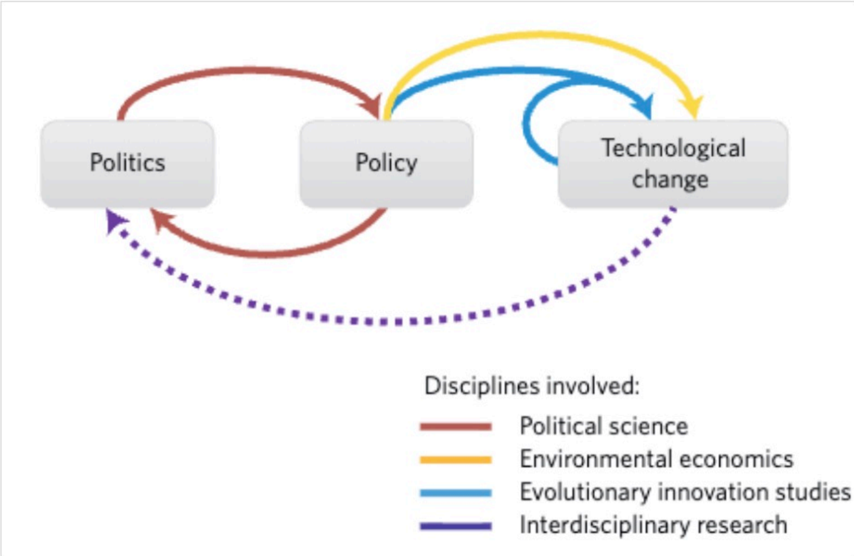

Figure 2.3: Feedbacks between technological change, policy, and politics.
Source: Schmidt and Sewerin (2017)

anticipating the consequences. As such, feedback loops — both intended and unintended — are intrinsic to policy making, contributing to what some have termed as ”compulsive policy-making” (Hoppmann et al. 2014). Furthermore, the political nature of policymaking is deeply intertwined with geography, **technology** characteristics, and the dynamics of actors, networks, and institutions surrounding it (Geels 2004; Schmidt and Sewerin 2017). For example, fossil fuel–dependent regions often resist decarbonisation efforts, while those with growing renewable energy industries are more likely to support them (Kuzemko et al. 2016). So, geography is not a neutral backdrop but a political variable that shapes coalition formation and interest alignment (Schmidt and Sewerin 2017). Similarly, technology characteristics also carry political implications. RE technologies empower new actors, challenging incumbent utilities tied to vertically integrated models, while technologies, like carbon capture and storage, reinforce fossil fuel-based power structures (Kivimaa and Kern 2016). As a result, technology choices are also politically driven (Schmidt and Sewerin 2017).

Additionally, **policy choices** made in earlier rounds of policymaking influence technological, political, and policy developments in later stages. Pierson (1993) refers to this dynamic as when ”the effect becomes the cause.” For example, early public investments, or the absence thereof, in one technology or adjacent sector can create both short- and long-term opportunity costs (Schmidt et al. 2016). In other words, backing a particular technology accelerates its cost reduction through learning effects but can foreclose alternatives, creating lock-in or setting a path that becomes difficult to reverse (Schmidt et al. 2016). Simultaneously, supporting a new technology can generate new political coalitions that advocate for continued or expanded support, reinforcing the technology in the socio-technical system, allowing space to raise political ambitions (Leipprand et al. 2020; Pahle et al. 2018; Sewerin et al. 2023). In contrast, increasing support for new technologies can also provoke backlash from incumbent actors, creating political contestation that undermines the continuation of policies favouring said technology, and thereby lowering political ambitions (Breetz et al. 2018; Edmondson et al. 2020; Patterson 2023). This connects to a broader sub-stream of literature debating the conditions under which political ambition ratchets up or down. Here, the design of optimal policy mixes — such as sequencing (Meckling et al. 2017; Pahle et al. 2018), layering (Laird 2016), dismantling (Gürtler et al. 2019; Schaub et al. 2024), and the role of institutions (Geels 2004), including their governance structures, and fiscal and administrative capacities (Edmondson et al. 2019) becomes central to arguments made. For example, Germany’s early solar subsidies fostered development; as technology costs fell and policy costs rose, support could be scaled back while still maintaining high solar ambitions Pahle et al. (2018). In contrast, Ohio’s RE policies were dismantled after early support led to a cost decline of these technologies, prompting opposition from coal-dominated utilities and large consumers (Breetz et al. 2018).

Feedback between technology and policy can also originate from **external sources**. These include the spatial diffusion of technology learning. For example, Germany’s early feed-in-tariff policy supported solar PV deployment. China capitalised on the growing demand for solar components by incentivising domestic module manufacturing. (Nemet 2019; Quitzow 2015b; Schmidt and Sewerin 2017). Similarly, there may also be a spatial diffusion of policy learning[6].

[6]Or policy proliferation.

For example, the rising fiscal burdens associated with sustaining feed-in tariffs, particularly for wind, led countries to transition toward auction-based support policies, both for the same and similar RE technologies like utility-scale solar (Leiren and Reimer 2022). Broader external events — such as economic crises, climate shocks, nuclear incidents, wars, or major technological breakthroughs — can also accelerate support for certain technologies or disrupt existing trajectories (Cherp et al. 2017; Jacobsson and Lauber 2006; Pavlenko and Cherp 2023). This dynamic — of how sudden exogenous shocks can realign policy priorities and reshape political coalitions. This has been commonly studied through the punctuated equilibrium theory in political science (Pierson 2000), or under the political perspectives in energy transition literature (Cherp et al. 2018).

2.2.2 Mapping technology growth and policy change

Mapping technology growth has had a long history, situated within the energy transitions literature, and has traditionally relied on quantitative methods (Griliches 1957; Grubler 1996; Hägerstrand 1976; Rogers 1983). There is general consensus that the evolution of technology growth over time follows an S-shaped trajectory — characterised by an initial slow uptake, steep growth during the middle phase, and eventual stabilisation (Rogers 2003). Each phase is shaped by a unique mix of techno-economic, socio-technical, and political mechanisms (Vinichenko 2018). See Figure 2.4. Recent research has highlighted that this S-curve can, in fact, be divided into four distinct phases rather than three (Jewell et al. 2025). The initial, or formative phase, is marked by high costs, significant uncertainty, frequent failures, and the absence of a clear dominant design (Abdulla et al. 2021). Adoption during this stage is limited to niche actors with low visibility, facing little opposition because the innovation's broader potential remains unclear (Breetz et al. 2018). This phase is dominated by experimentation, learning, and trial-and-error, resulting in slow and uneven growth (Bento et al. 2018). After a period of continuous experimentation and learning, the technology crosses a threshold — a point of take-off (Cherp et al. 2021; Markard 2018). This threshold is often defined as reaching approximately 0.5–2.5% of the total market share (Jewell et al. 2025). At this stage, the acceleration phase begins, where growth becomes exponential, with each year adding more capacity than the last. This phase is characterised by initially high but rapidly declining costs, growing profitability, and the emergence of strong positive feedbacks: lower costs drive greater deployment, which leads to more learning and further cost reductions, essentially following Wright's Law (Arthur 1994). Globally, solar PV is currently in this acceleration phase (IEA 2023b). Market-driven proponents argue that achieving take-off unlocks a technology's self-sustaining growth, allowing expansion with little or no further policy support (Creutzig et al. 2017), and they often assume this phase will persist for an extended period (Trancik et al. 2015; Victoria et al. 2021; Way et al. 2021).

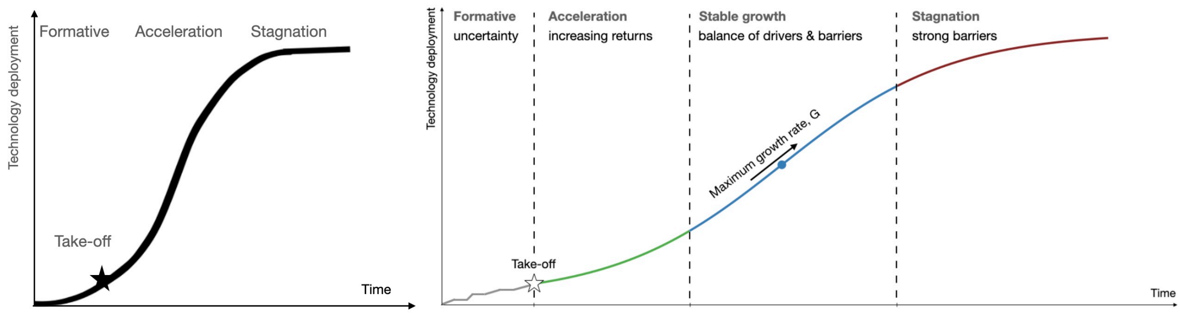

Figure 2.4: Simple illustration of the three phases (left panel) and the four phases (right panel) of technology growth.
Source: Own illustration on the left panel based on Rogers (1983) and Cherp et al. (2021). The right panel figure is from Jewell (2024)

However, proponents of the four-phase model argue that the acceleration phase is (actually) short-lived. Technologies soon reach an inflection point where growth slows from exponential to linear (Hansen et al. 2017), entering a stable growth phase characterised by a more even balance between drivers and barriers (Jewell et al. 2025). In this stable phase, growth is no longer propelled solely by positive cost-driven dynamics. Instead, it increasingly contends with barriers, like public opposition (Vinichenko 2018). Capacity additions become relatively steady from year to year on average in the long-term, with growth evolving in pulses — alternating between periods of acceleration and deceleration (Jewell et al. 2025; Kulmer et al. 2022; Vetier et al. 2025). Cost reductions also decelerate, as each doubling of output requires significantly larger absolute deployment volumes to sustain previous learning rates (Jewell et al. 2025). Eventually, as barriers become more entrenched and harder to overcome, the technology enters a saturation phase where adoption slows significantly or halts entirely (Rotmans et al. 2001; Vinichenko 2018). Market share plateaus, and further expansion becomes minimal. Globally, nuclear energy has been in this saturation phase since the 1980s (Jewell et al. 2025).

Mapping policy change also has a long history, drawing from political science and policy analysis, and has traditionally relied on both quantitative and qualitative case study approaches (Hall 1993; Sabatier 1991). Studies in this area are diverse, mapping the relationship between specific policy interventions and various climate mitigation outcomes (Hoppe et al. 2023; Stechemesser et al. 2024), including technology growth (Edmondson et al. 2020; Kilinc-Ata 2016; Suzuki et al. 2023; Weber and Rohracher 2012). Research has ranged from focusing on policy needs at particular points in time (Breetz et al. 2018; Edmondson et al. 2019; Markard 2018; Nijsse et al. 2023; Ollier et al. 2024), to examining how and why policies evolve (Grubb et al. 2015; Turnheim and Geels 2013), and assessing their effectiveness in achieving different outcomes (Kern et al. 2015). Traditionally, scholars have interpreted policies in two ways: by their aims or "targets" (the goals they seek to achieve), and by the tools or "instruments" they use to reach those goals (Cashore and Howlett 2007; Hall 1993). In the literature, these are often referred to as policy priorities and policy instruments, respectively (Ollier et al. 2024).

However, much of the work on policy change has focused more on the latter — studying specific instruments (e.g., carbon pricing and feed-in tariffs) (Hoppmann et al. 2014; Weber and Rohracher 2012) or broader clusters of instruments such as regulations (Borrás and Edquist 2013; Knill et al. 2012). See Figure 2.5.A more recent development has argued for shifting attention from single instrument or instrument types to studying entire policy mixes or policy portfolios (inclusive of different instrument types and clusters), recognising that different instruments interact and influence one another (Rogge and Reichardt 2016) in ways that affect

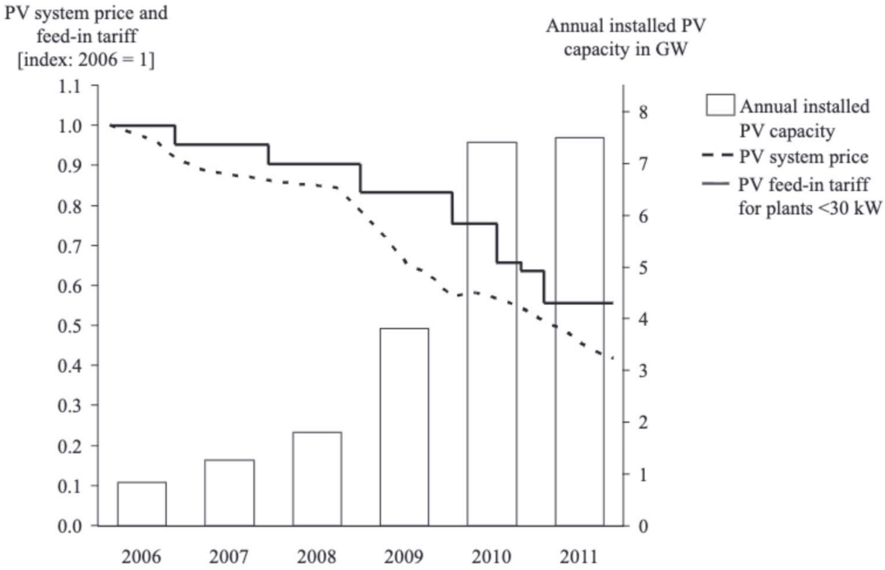

Figure 2.5: Change in feed-in tariff, PV system price, and annual installed capacity for solar PV in Germany between 2006-2011.
Source: Hoppmann et al. (2014)

outcomes. Researchers have tracked the evolution of these policy mixes over time, analysing characteristics like diversity, density, stringency, intensity, and sequencing (Knill and Tosun 2012; Li et al. 2025; Nachtigall et al. 2022; Pahle et al. 2018; Schmidt and Sewerin 2019; Sewerin et al. 2023) to assess their effectiveness in achieving specific outcomes. In these analysis, while there is broad agreement that "no single silver bullet" (Rogge et al. 2017) mix exists, one key feature of analysis is identifying what design elements make up an effective and sustainable policy mix (Edmondson et al. 2025). For example, an optimal policy mix should consider interactions among instruments, account for the roles of actors and institutions, manage path dependencies by strategically introducing, adjusting, or removing policies to avoid lock-ins, and address multiple barriers at both market and system levels (Edmondson et al. 2025; Howlett and Rayner 2007; Rogge et al. 2017).

In contrast, attention to policy priorities has been limited but is gradually emerging (Ollier et al. 2024; Oosthuizen and Inglesi-Lotz 2022). The focus on policy priorities takes a broader, high-level approach. It builds on the recognition that policymakers, with their limited resources, often pursue multiple priorities simultaneously, which may or may not be technology-specific and are often highly context-dependent, and these priorities shift over time and can either be congruent or conflicting with one another (Hall 1993; Ollier et al. 2020; Schmidt et al. 2019). While not explicitly focused on policy priorities, Quitzow (2015a) has introduced the concept of policy strategy, emphasising whether different strategies within a policy mix are congruent and aligned with a long-term transition vision. Though these studies do not explicitly frame their work around policy priorities, their conceptualisation closely aligns with the idea that the effectiveness of the policy mix can also be measured based on the alignment of overarching goals or "visions" within the mix, rather than simply focusing on instruments (Quitzow 2015b).

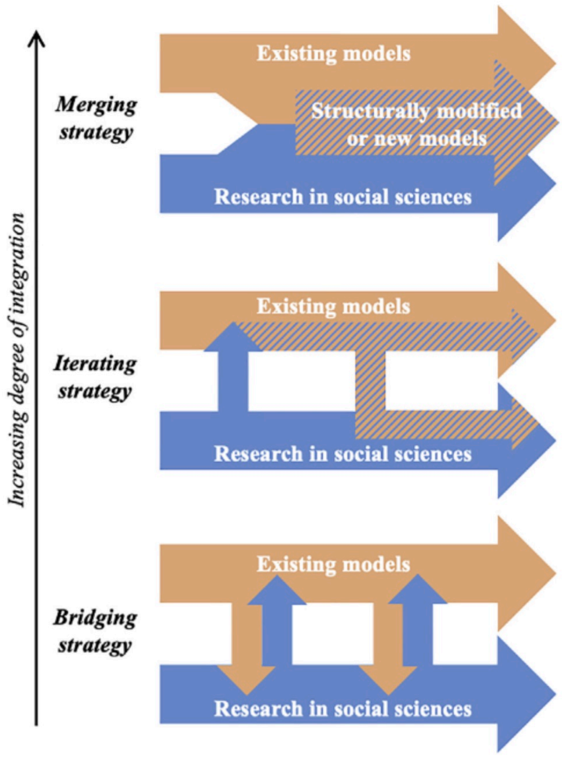

Figure 2.6: The three strategies for linking energy models and insights from social sciences. *Source: Trutnevyte et al. (2019)*

The research bridging the fields of technology growth and policy change in the context of climate mitigation remains limited. Much of the existing work primarily focuses on different climate scenario modelling exercises, which map the evolution of policies to mitigate climate change by projecting future technology growth based on techno-economic parameters, particularly technology costs (Iyer et al. 2022; Soest et al. 2021). However, these models have been significantly criticised for relying on overly unrealistic assumptions (Smil 2008), and overlooking the complex socio-political feedbacks that emerge from the interaction between technology, policy, and politics (Geels et al. 2016; Jewell and Cherp 2023; Trutnevyte et al. 2019). In other words, socio-technical and political factors that influence technology adoption are often neglected, leading to inaccurate projections that either overestimate or underestimate growth, thereby providing policymakers with misleading signals about the level and type of policy support needed (Kotchen et al. 2023; Luderer et al. 2022). Recent scholarship has proposed a merging strategy instead of a bridging approach, where key societal factors can be modelled Trutnevyte et al. (2019). See Figure 2.6. Yet, the application of these new types of models remains very limited, and thus their ability to provide practical policy options Hirt et al. (2020). To model societal factors, it is important to know what these are and how they are structured along the S-shaped path of technology growth. Studies have aligned different types of policy needs appropriate for different technology phases. However, these analyses have been somewhat abstract and non-systematic (see Breetz et al. (2018)), and if systematic, not holistic (see Ollier et al. (2024)). In other words, studies have not previously quantified the intensity of policy needs with distinct technology growth phases, or assessed them holistically as a share of the total policy mix. Plus, they remain primarily focused on developed country contexts, a sentiment also expressed in Breetz et al. (2018)

2.3 Renewable energy transitions in developing countries

Narratives on RE transitions in developing countries have been influenced by the North–South divide in global climate governance. It essentially surrounds the contrasting socio-economic capacities and priorities between the two. I introduce these narratives, including the relevant debates, in Section 2.3.1. Before proceeding, it is important to clarify the use of the term "developing countries", which has widely been debated (Escobar 2011). Alternatives like "emerging markets and developing economies" (used by the OECD) or "Global South" (sometimes used alternatively in literature) or "emerging economies" (sometimes also referring specifically to

BRICS[7] countries) exist (Farias 2024). Yet, here I borrow from the World Bank (2024) classification. It defines developing countries as those with low- and middle-income levels, based on per capita gross national income. As of 2025, this group includes 131 countries. While not engaging in the debate on the term's appropriateness, I acknowledge the criticism it draws, both on normative assumptions and especially its broad generalisation. India, due to its economic size and geopolitical role, receives particular attention in both academic and policy discussions. However, given that this dissertation focuses on India, the review draws on the broader context of RE transitions in developing countries that share comparable characteristics. The idea here is that, while these countries differ in many ways, they often face comparable challenges and share common narratives in the technology growth and RE transition literature (Hansen et al. 2018).

2.3.1 Narratives around RE transitions

Since the 1990s, global climate governance debates have emphasised the historical responsibility of developed countries for the bulk of greenhouse gas emissions (Rajamani 2000). Under the principle of common but differentiated responsibilities, developing countries are recognised as having the right to pursue economic growth without bearing a disproportionate share of the mitigation burden (Rajamani 2000). At the same time, these countries are among the most vulnerable to climate change due to their geographic exposure and constrained adaptive capacities (IPCC 2022). Plus, rapid economic growth, urbanisation, and demographic pressures are driving up emissions here and are likely to continue doing so (IPCC 2022). As a result, efforts to decarbonise developing countries are seen as essential to limit global warming, making the widespread adoption of RE technologies in these regions increasingly urgent (IEA 2021b; IPCC 2023; Pfeiffer and Mulder 2013; Sachs et al. 2019).

RE technologies — such as hydro (both large and small), solar, and biogas — have long existed

[7] BRICS includes 11 countries: Brasil, Russia, India, China, South Africa, Saudi Arabia, Egypt, United Arab Emirates, Ethiopia, Indonesia, and Iran.

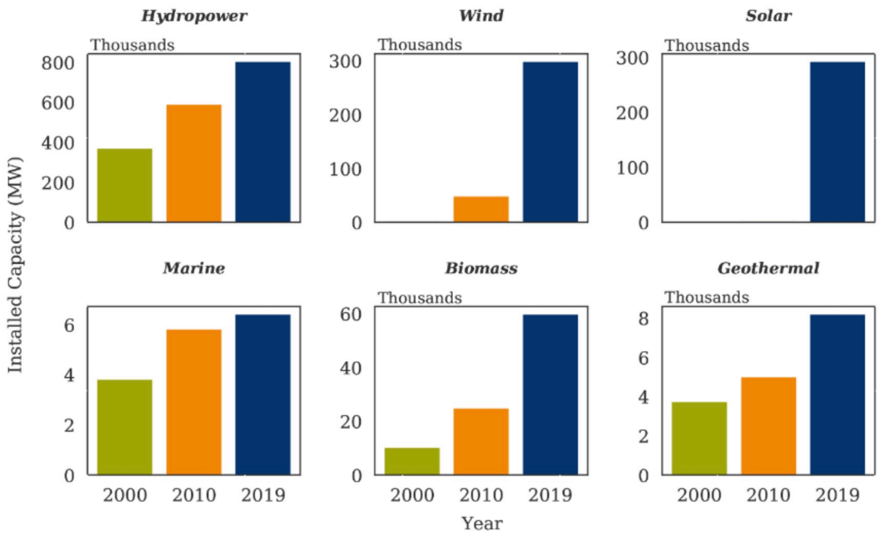

Figure 2.7: Change in installed capacity of RE technologies in developing countries between 2000-2019.
Source: Cantarero (2020)

in many of these countries, often in decentralised and traditional forms. See Figure 2.7. However, aside from large-scale hydro, these technologies have not been sufficiently modernised or scaled to meet growing energy demand (Pfeiffer and Mulder 2013). Socio-economic, cultural, and political conditions have led to innovations here historically following an incremental and adaptive trajectory rather than one led by formal R&D (Lundvall et al. 2011). This is largely due to higher investment risks, limited financial and institutional capacities, lower formal education levels, and a reliance on several small, cumulative innovations (Hansen et al. 2018; Zanello et al. 2016). Much economic activity also takes place in the informal sector, which fragments innovation processes and limits scaling (Hansen et al. 2018; Lund 2006). Bhatti and Ventresca (2012) describe innovation in these settings as often being "frugal" or "grassroots" — low-cost, resource-efficient, and tailored to local needs, particularly for low-income communities[8]. As a result, firms in developing countries often lack the resources or incentives for in-house R&D and instead adapt technologies developed externally (Zanello et al. 2016). This contrasts with developed countries, where innovation is typically tied to formal R&D investments, design engineering, and improving process efficiencies — aimed at yielding both transformative and scalable outcomes (Hansen et al. 2018).

[8]For example, the Indian concept of "*jugaad*" illustrates this phenomenon (Gulati 2010).

Therefore, due to the differing nature of innovation, their historical responsibility for emissions, and their greater economic and technological capacities, developed countries are expected to lead climate mitigation efforts and support developing countries. Two widely discussed approaches are technology transfer and climate investments — where innovations originate in the developed world and are then transferred to developing regions, or developed countries help finance such projects in the latter (Popp 2011). This also opens up the possibility for developing countries to "leapfrog" directly to low-carbon technologies, bypassing the carbon-intensive development path previously followed by the former (Goldemberg et al. 1987). However, the leapfrogging narrative remains contested. While some view it as a promising strategy to close the technological and economic development gaps (Ram et al. 2022), others are more cautious. They point to structural, institutional, and socio-economic constraints that may limit its actual transformative potential (Yap et al. 2022).

2.3.2 Debates around technological leapfrogging

The term "technological leapfrogging" first emerged in the late 1980s, amid growing discussions over how developed and developing countries could collaborate to address climate change (Goldemberg et al. 1987). A clear distinction was made between technological learning and innovation versus technological leapfrogging. The former involves continuous, incremental improvements that lead to successive breakthroughs and the eventual replacement of earlier technologies, typical of technological evolution in developed countries (Goldemberg et al. 1987). The latter entails the transfer of advanced technologies from developed to developing nations, where "still older versions of technology are prevalent, if they exist at all" (Goldemberg et al. 1987). Nevertheless, leapfrogging implicitly incorporates elements of the former, as adopting advanced technologies in one area requires prior technological learning in another. Hence, both processes share a core aspect that has been extensively studied in the long tradition of geography and diffusions of innovations — namely, how technologies and innovations grow and spread across space. I review this broader literature in the next section, while here I focus on arguments solely aligning with developing country contexts.

Studies on technological leapfrogging range from exploring its potential benefits in developing countries (Gulagi et al. 2022), to examining the different modes through which it occurs — such as international trade, skilled migration, research collaboration, digital knowledge flows, FDI, licensing, joint ventures, and integration with global value chains (Fu et al. 2011). These studies also include lessons from successful and unsuccessful cases (Athreye and Godley 2009; Fu et al. 2011; Fu and Zhang 2011; Lee 2021) and ways to optimise the process (Yap et al. 2022). Broadly, there are two main positions.

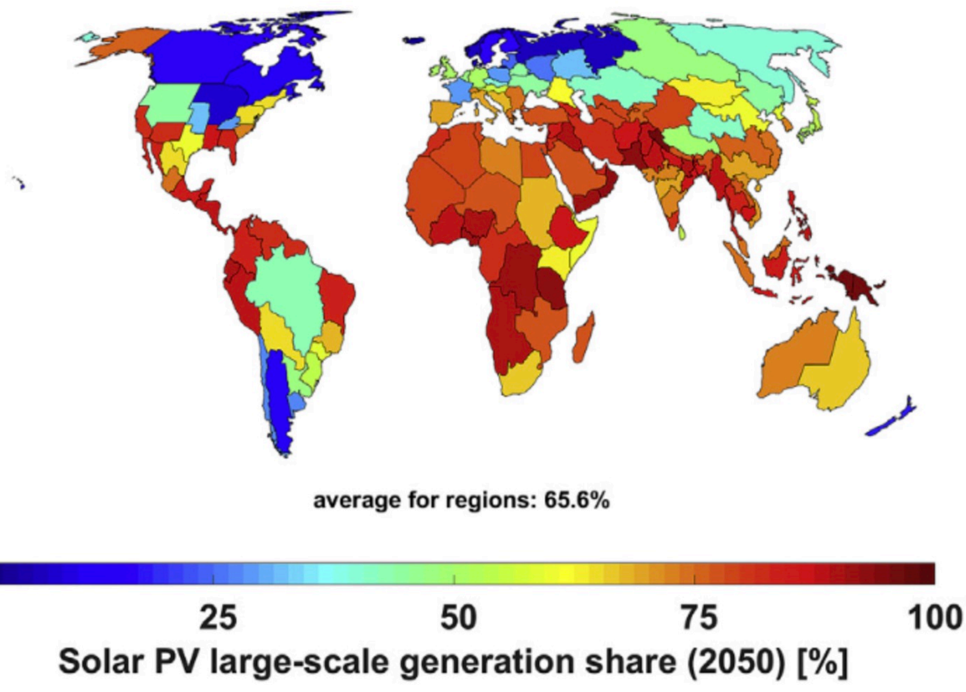

Figure 2.8: Projected global share of electricity generation from large-scale solar PV in 2050 under an optimistic technology leapfrogging scenario.
Source: Bogdanov et al. (2021)

The first is **an optimistic view** (Arndt et al. 2019; Bogdanov et al. 2021; Gulagi et al. 2022; Ram et al. 2022) that builds on three key points. (i) RE potential in developing countries is high, due to abundant natural resources such as sunlight and wind, making these technologies particularly suitable in these regions; (ii) the growing size of economies and energy systems creates opportunities to integrate RE technologies into expanding demand, avoiding the more difficult challenge of substituting existing infrastructure; and (iii) developing countries today have access to advanced and efficient technologies that were not available to richer countries when they were at similar stages of economic development. These geographic and economic advantages, combined with the availability of modern technologies, enable countries to avoid locking into costly and polluting fossil fuel-based systems (Goldemberg et al. 1987). This also opens pathways to bridge the economic development gap or ”catch up”, and in turn results in high levels of RE penetration and decarbonisation at relatively low costs (Gulagi et al. 2022; Hansen et al. 2019; Ram et al. 2022). See Figure 2.8. As such, leapfrogging addresses multiple challenges in developing countries simultaneously — affordability, accessibility, energy security, and sustainability — without hindering economic growth (Arndt et al. 2019). Furthermore, widespread adoption can accelerate global technological learning, further reducing costs and creating a self-reinforcing cycle of innovation, cost decline, and growth (Bogdanov et al. 2021; Victoria et al. 2021). This optimistic view aligns with market-driven arguments for energy transitions discussed in Section 2.1.1, focusing on the dominant role of technological and cost-based factors in energy transitions.

Critics of the optimistic view often overlap with those arguing that energy transitions are primarily policy-driven (Section 2.1.2). They contend that the optimistic leapfrogging arguments frequently overlook the socio-economic and political realities of recipient countries (Afful-Dadzie 2021; Fu and Zhang 2011; Gallagher 2006; Hansen et al. 2018). First, leapfrogging assumes a level of institutional and socio-political capacity (equal to that in rich technology pioneers), which is often lacking in developing countries (Hansen et al. 2018; Ramos-Mejía et al. 2018; Wieczorek 2018). Weak governance has hindered innovation in India’s biomass gasification (Schmidt and Dabur 2014), while the presence of informal sectors, such as in Bangkok’s transport sector, created further complications (Sengers and Raven 2015). Plus, corruption, lack of transparency, and elite capture — where powerful actors shape policy to serve their interests — are also persistent barriers. For example, Swilling et al. (2015) finds that RE initiatives in South Africa disproportionately benefited elites and marginalised poorer communities, limiting technological diffusion and reinforcing inequality. Another important aspect is the ingrained behavioural and cultural practices in developing countries. For example, Cantarero (2020) finds that the residential sector in these regions remains largely reliant on traditional solid biofuels. Even when households have access to improved, cleaner energy alternatives, solid biofuels are not fully replaced. Instead, there is evidence of a combined use of both modern and traditional technologies — a phenomenon known as "fuel stacking" (Ruiz-Mercado and Masera 2015).

Second, while technology transfer and FDI are central to leapfrogging, establishing strong external linkages without internal capacity-building, knowledge sharing, local technology learning, and local value chain development, donor-driven projects often remain isolated pilots, entrenching external dependencies, and limiting scale-up (Hansen et al. 2018; Malhotra et al. 2019; Nygaard and Hansen 2015; Schmidt and Huenteler 2016; Wieczorek 2018). This is seen in Kenya's wind sector (Kamp and Vanheule 2015). Poor sequencing and over-reliance on imports can also provoke resistance from domestic industries and hinder long-term development, as we will see in the solar PV sector in India (Behuria 2020). By contrast, in rare successful cases like solar PV in China (Figure 2.9), leapfrogging went beyond simple technology transfer but involved complex, multi-layered processes dependent on developing strong external linkages and robust internal capacities (Fu and Zhang 2011). It involved sustained domestic innovation, R&D, and coordinated industry and trade policies. These processes included sequencing multiple technology transfers simultaneously, iterative learning, and long-term commitment — demanding deeper systemic engagement rather than passive adoption. Finally, this group argues that conventional leapfrogging narratives rely on linear and established, catch-up models of development (Gallagher 2006; Yap et al. 2022). Addressing grand societal challenges like climate change requires "transformative leapfrogging" (Yap et al. 2022), which calls for context-sensitive models rooted in local capacities, systemic innovation, and institutional reform. Central to this is shaping the "selection environment" through improving innovation system functions by building legitimacy, inclusive markets, and steering investment toward just and sustainable futures (Bergek et al. 2008; Yap and Truffer 2019).

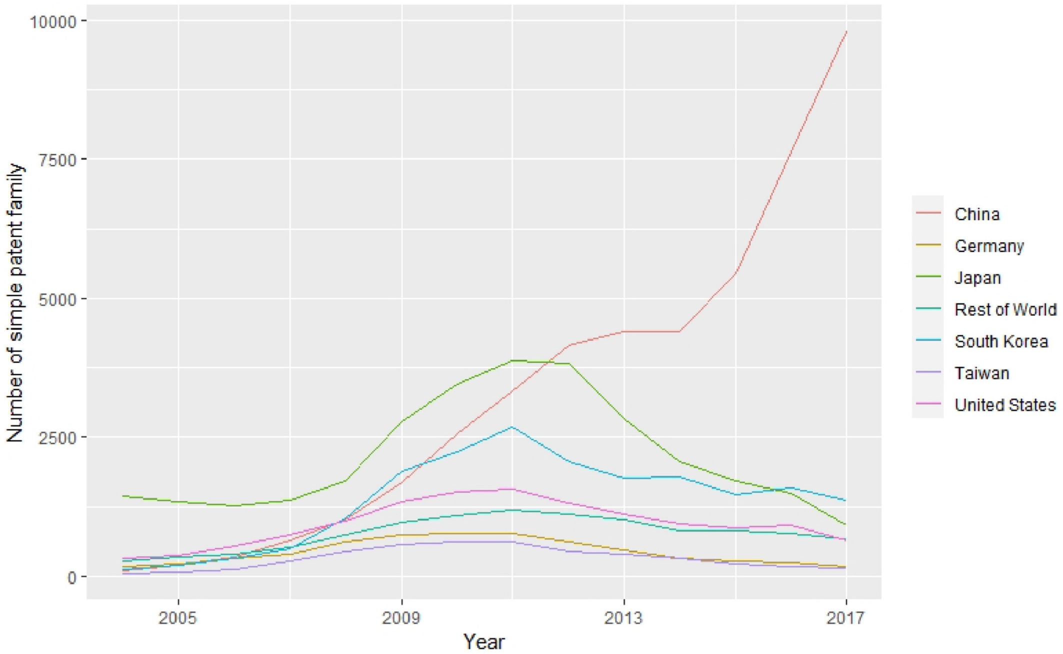

Figure 2.9: Change in solar PV patents in major manufacturing countries between 2004-2017. *Source: Yap et al. (2022)*

2.3.3 Barriers to RE transition in developing countries

Critics of the overly optimistic view on technological leapfrogging highlight a few persistent and sticky challenges in developing countries. A key concern is the limited institutional and infrastructural capacity **in the electricity sector** — the very sector where the RE transition must occur. In many cases, electricity systems were initially introduced by foreign actors, with infrastructure designed to serve their interests rather than through centralised planning for long-term societal development (Williams and Ghanadan 2006). This differs from electricity systems in wealthier nations, which evolved through domestic innovation, industrialisation, broader development goals, and sometimes coordinated military imperatives (Pomp 2000; Power 2022). After World War II and decolonisation, nationalised, vertically integrated electricity systems became the global norm (Urpelainen and Yang 2019). However, many newly independent states lost the institutional knowledge previously held by foreign actors (Acemoglu et al. 2001), weakening their ability to manage and expand these systems effectively. This, plus the global shift toward electricity liberalisation in the 1980s–90s (Urpelainen and Yang 2019; Williams and Ghanadan 2006) and the concurrent emergence of complex governance structures, further entrenched institutional weaknesses. These deeply embedded and mutually reinforcing challenges persist, leaving the sector with enduring capacity and operational issues, despite decades of reform (Chaturvedi et al. 2024).

The challenges have manifested in persistent inefficiencies across power procurement, scheduling, and dispatch (Cantarero 2020). At the wholesale level, limited electricity trade and a reliance on rigid bilateral contracts constrain merit-order dispatch (Chaturvedi et al. 2024), preventing systems from fully leveraging or embracing innovation. These rigid contracts, in turn, lead to higher power purchase costs, which are compounded by distorted tariff structures such as cross-subsidies and non-cost-reflective pricing, and inefficiencies in metering, billing, and revenue collection - further erode the financial viability of distribution utilities (Cantarero 2020; Chaturvedi et al. 2024; Dubash et al. 2018; Huenteler et al. 2017). This, in turn, undermines their ability and incentive to support RE, invest in infrastructure, or facilitate system upgrades (Salama and Al-Sumaiti 2014). They also hinder prosumer participation at the retail level, which has been a key driver of solar PV adoption in developed countries. Unlike in the latter, where prosumer solar reflects climate awareness, profitability, and enhanced grid flexibility (Hansen et al. 2022), developing countries face low public enthusiasm, affordability barriers, and inflexible grids, resulting in limited policy support for awareness programs aimed at broadening the adopter base (Khan 2019). Thus, on an infrastructural level, inadequate grid capacity prevents RE techno-economic gains from translating into scalable deployment. This leads to poor coordination, limited regional resource sharing, and inefficient asset utilisation, leading to load-shedding, voltage fluctuations, and blackouts as in India (Verma et al. 2020) or curtailment issues as in China (Xia et al. 2020).

Beyond the power sector, developing countries face broader socio-economic and political challenges. RE planning processes often remain top-down, with limited citizen participation. Public engagement — vital for driving distributed energy solutions and climate advocacy in many OECD countries — is frequently absent. Plus, in contrast to the latter, where high-quality, tax-funded public services foster political legitimacy and accountability, many developing countries contend with corruption, lack of transparency, and weak institutions (Hansen et al. 2018), making it difficult to manage the complex demands of the RE transition or create a supportive environment for technological leapfrogging. For example, institutional limitations complicate land access. Although land may be cheaper in developing countries, it is often contested due to unclear property rights, competing land-use demands in rapidly growing economies, culturally embedded landownership norms, and a long history of political resistance along socio-economic lines (Meyfroidt et al. 2022; Nielsen et al. 2020). Land thus becomes a site of political contestation — an issue magnified by weak institutions and contributing to what many have argued as persistent inequalities (Lakhanpal 2019; Lamhamedi and Vries 2022; McEwan 2017; Yenneti 2016).

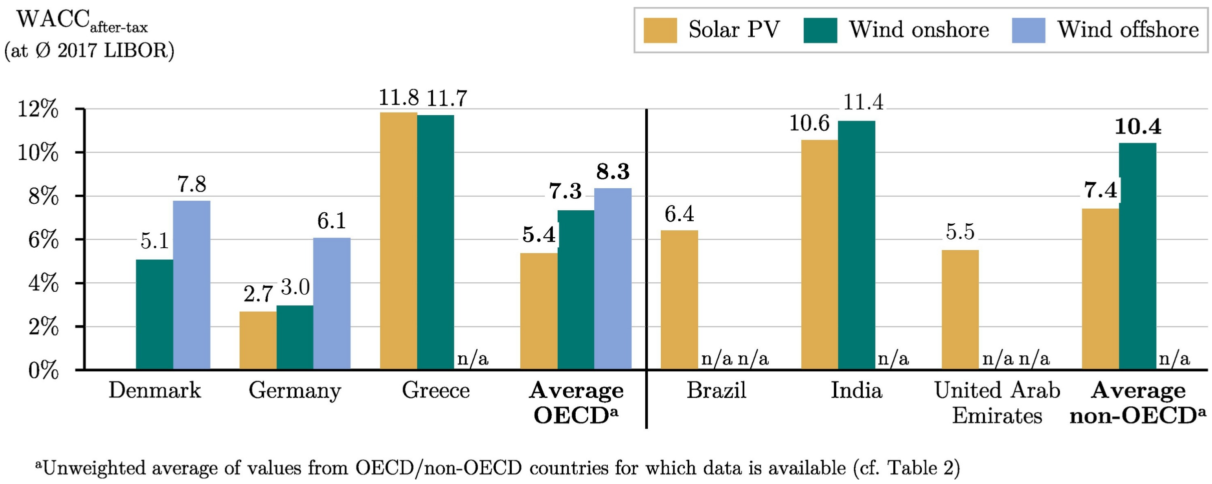

Figure 2.10: Weighted average cost of capital in OECD and non-OECD countries for solar and wind.
Source: Steffen (2020).

Another major issue (frequently cited in leapfrogging debates) is that the absence of strong local conditions inhibits developing countries' ability to absorb or increase accessibility to foreign climate finance (Ameli et al. 2021). Here, the scholarship finds that weak economies, low business confidence, policy uncertainty, and inadequate regulation in these countries deter investment (Ameli et al. 2020; Egli et al. 2019). Plus, underdeveloped capital markets and limited financial resources make affordable finance difficult to access (Ameli et al. 2021). This is particularly problematic for RE projects, which require high upfront capital (Egli et al. 2018; Hirth and Steckel 2016; Steffen 2020) and often face bankability issues due to pricing distortions and power utilities' revenue inefficiencies (Huenteler et al. 2017). To offset these risks, investors apply high premiums, leading to increased financing costs (i.e., higher weighted average costs of capital) (Ameli et al. 2021). See Figure 2.10. Combined with investor "home bias" toward domestic markets (Buchner et al. 2019), these factors create what Ameli et al. (2021) describe as a "climate investment trap" — a self-reinforcing cycle where low investment delays the transition, heightens risk, and further discourages capital inflow. See Figure 2.11. The result is that it makes the leapfrogging pathway even more challenging and costly (Ameli et al. 2021).

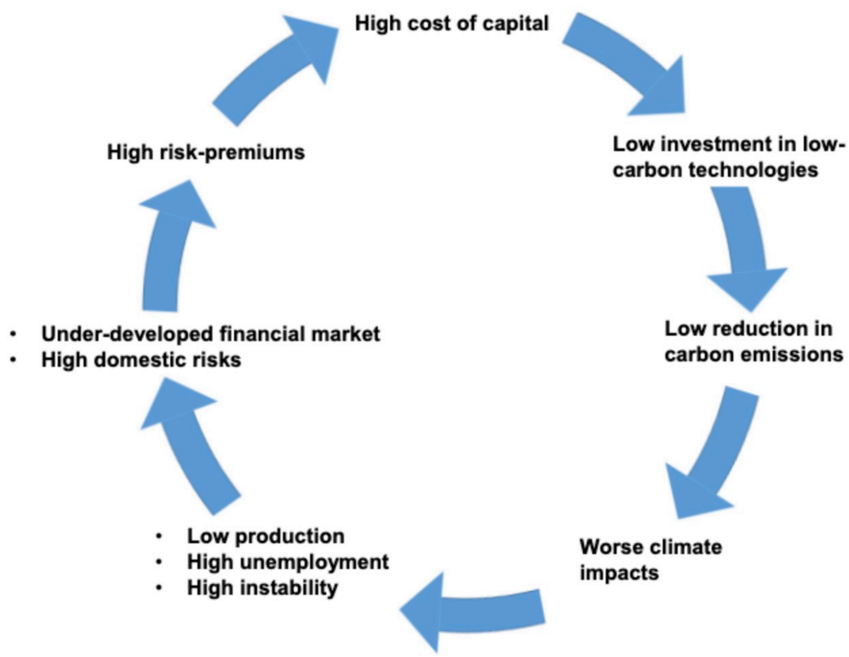

Figure 2.11: The climate investment trap in developing countries.
Source: Ameli et al. (2021)

While the literature on RE transitions has debated whether technological leapfrogging can enable developing countries to bypass fossil-intensive development, less attention has been paid to how the prevalence of barriers shapes the sequencing of policy support needed to accelerate RE in these recipient contexts. In other words, on the one hand, the question remains whether leapfrogging works at all, given the institutional, infrastructural, and financial constraints that differentiate recipient countries from pioneers. On the other hand, what is under-explored is how these barriers should be conceptualised at different stages of technological growth, and how their timing interacts with choices policymakers face. Much of the existing work frames leapfrogging in binary terms — optimism about cost declines and abundant resources versus pessimism about structural constraints — without examining how they shape the scale and persistence of policy support needed to drive RE growth in recipient contexts.

2.4 Spatial patterns in technology growth

The literature on the spatial patterns of technology growth and that on technological leapfrogging largely overlap in their central concern: whether technology recipients can grow faster than technology pioneers. However, there is a subtle distinction in their temporal origins and geographical scope. While the leapfrogging literature typically frames this debate in the context of RE transition in today's developing countries (Goldemberg 1998), the spatial diffusion of innovation literature adopts a more universal and global outlook (Bell and Pavitt 1993; Gerschenkron 1962; Grubler 1990; Lee and Lim 2001; Perez 1985). Both encompass catch-up in terms of economic development, factor productivity, industrial development, and overall technological growth. See also (Kremer et al. 2022). In fact, the leapfrogging conceptualisation can be seen as an extension of the spatial diffusion literature, which originated earlier in the 1950s through post-World War II studies of late-industrialising countries. Widely cited examples from that time remain how Japan and South Korea were able to catch up with early industrial leaders (Lee and Lim 2001). These were then subsequently used to substantiate the technology leapfrogging and RE transition work.

In this final review section, I focus on the broader spatial technology diffusion literature: first, assessing what it says about the factors driving technology growth across space, and second, capturing the core arguments on whether later adopters can "catch up" to early adopters in the pace and scale of technological growth.

2.4.1 Factors affecting spatial patterns in technology growth

The first seminal work on spatial diffusion of innovation can be traced to Griliches (1957) and Hägerstrand (1976). Hägerstrand (1976) (p. 53), a Swedish geographer, examined how agricultural technologies and farming practices spread across southern Sweden during the 20th-century post-war modernisation era. He introduced the concept of the "contagion" or neighbourhood effect, where innovations diffuse outward from central "innovation centers" — what later scholars like Grubler (1996); Wilson (2012) have called "core" or early-adopting markets — to surrounding "rim" and "periphery" or later-adopting areas. According to this effect, individuals are more likely to adopt an innovation if their neighbours or nearby contacts have done so, as seen in the village-level uptake of high-yield crops based on local demonstration and peer influence. Hägerstrand also described a hierarchical diffusion pattern, where innovations spread not only locally but also leapt from larger cities to smaller towns, following socio-economic hierarchies — such as how specialised tractors initially gained traction in major urban centres before gradually reaching rural areas. He argued that these processes produce discernible spatial patterns — typically in wave-like movements radiating outward from the origin, with the likelihood of adoption decreasing with distance from the innovation source due to diminishing exposure and social influence[9].

The significance of geographic proximity continues to be upheld in recent studies. For example, Keller (2002), Comin et al. (2012), and Bahar et al. (2014) emphasise the neighbourhood effect, while Keller (2010), Fatima (2017), and Halkos and Skouloudis (2021) highlight the role

[9]For a replication of this conceptualisation in the Indian solar case, see Figure 4.3.

of international trade and finance. Keller explains how geographic proximity manifests in both these factors: first, communication matters (also in Rogers (1983)). Face-to-face interaction is often necessary for transmitting complex, tacit knowledge, making geographic closeness essential. Second, trade and technology transfer go hand-in-hand, particularly through multinational firms, meaning that if it is costly to trade with a country, it is also costly to transfer technology to it.

Zanello et al. (2016) highlight how constraints in infrastructure that facilitate different forms of communication, trade and investment can increase geographic distance. Comin and Hobijn (2004) highlight socio-economic conditions influence 'when' countries' adopt a new technology. Additionally, Lee et al. (2013) examine how cultural differences between countries like the U.S. and South Korea shaped mobile phone adoption patterns, showing that in individualistic cultures, innovation-driven adoption is more prominent (where individuals seek information independently through formal sources), while in collectivistic cultures, imitation plays a stronger role (where individuals rely more on informal, peer-based evaluations of new technologies). Others have explored how policy aligned with country-specific factors explains differences in spatial diffusion. For example, Andrews et al. (2015) highlight how firm-level and industry-specific factors — shaped in part by national policies — can determine a country's ability to innovate and adopt new technologies. Dechezleprêtre et al. (2015) focus on environmental regulation and find that it is not the stringency but the similarity of low-emission automobile policies across countries that influences cross-border diffusion of cleaner transportation technologies. They call it the "regulatory distance". Finally, Hughes and Meckling (2017) show how differing political preferences influenced policymaking in the U.S. and China, significantly shaped trade between the two, and how the solar PV and the industry subsequently evolved in each country.

Besides these national studies, sub-national analyses — across provinces, states, cities, and between urban and rural areas, also exist[10] (Dharshing 2017; Frantál and Nováková 2019; Griliches 1957; Hägerstrand 1976; Möller 2010; Xie et al. 2018; Yan et al. 2019). See also Table 4.1, specifically focused on solar in India. These have focused on the influence of economic, demographic, geographical, political, and local policy factors within the overarching commonality of a national context. For example, Rahmad et al. (2025) show how local social and political factors determine the differences in onshore wind adoption in Sweden. Others have controlled for these local factors, aiming to identify which types of policies lead to higher technology uptake. For instance, Shrimali et al. (2020) demonstrate that solar PV uptake across Indian states is influenced by land policies and higher renewable purchase obligations imposed on state distribution utilities. Some studies suggest it is a combination of both local factors and nationally enabling policies. Song and Han (2022) analyse green technology adoption across Chinese provinces and find that FDI plays a significant role, though its effectiveness depends on local industrial capacity and the presence of targeted government incentives. The range of literature here includes both cross-sectional and longitudinal perspectives. However, the role of geographical closeness is less explicitly explored, although it may be implicitly tied to frequently explored factors such as resource availability or market potential (e.g., population density, sector-specific electricity demand, etc.).

In other words, technology growth across regions is influenced by a wide range of factors, and a substantial body of literature — including on solar PV in India — has sought to capture these dynamics. However, differences in analytical approaches often make direct comparisons between studies difficult. Importantly, the diversity of local attributes means that any analysis of technological learning and policy support in driving the spatial diffusion of a technology must account for these regional peculiarities, as they mutually shape how diffusion unfolds.

[10] To name a few.

2.4.2 Pace of transition between early and later adopting regions

Finally, the speed at which later-adopting markets can grow and catch up with early adopters has been widely studied in the diffusion of innovation literature. Dating back to early seminal work, Hägerstrand (1976) illustrated that while innovations tend to spread in wave-like movements from core regions, they follow distinct S-shaped adoption trajectories within individual contexts over time. In other words, spatial diffusion inherently involves temporal dynamics (Griliches 1957; Grubler 1996). More recently, as stated earlier, this line of inquiry has gained relevance in the context of low-carbon energy transitions. Studies have attempted to extrapolate from both similar and contrasting technological cases to assess the possibility of rapid diffusion and growth in this domain (Grubler et al. 2016; Wilson et al. 2013). From a policy perspective, this discussion intersects with a critical question: to what extent can global techno-economic trends alone deliver us from climate catastrophe, and how much must be achieved through deliberate policy intervention?

Three main positions have emerged within this literature, stemming from what Cherp et al. (2021) frames as a tension between two opposing forces: technology learning and local context. While unfavourable conditions in late-adopting countries may hinder the uptake of new technologies, knowledge spillovers from early adopters can accelerate adoption and scaling. Scholars have sought to understand these dynamics geographically by examining factors contributing to installation over time, achieving different thresholds of growth like "take-off," and the time it takes technologies to move from early adoption to widespread saturation (Vinichenko 2018; Wilson et al. 2013).

The first position is the view, where **learning advantage dominates**. It emphasises the benefits of increasing global learning and experience, centred in early-adopting regions. Proponents argue that while late adopters initially lag, they can achieve faster growth once the technology reaches them, benefiting from the accumulated knowledge and improvements made elsewhere.

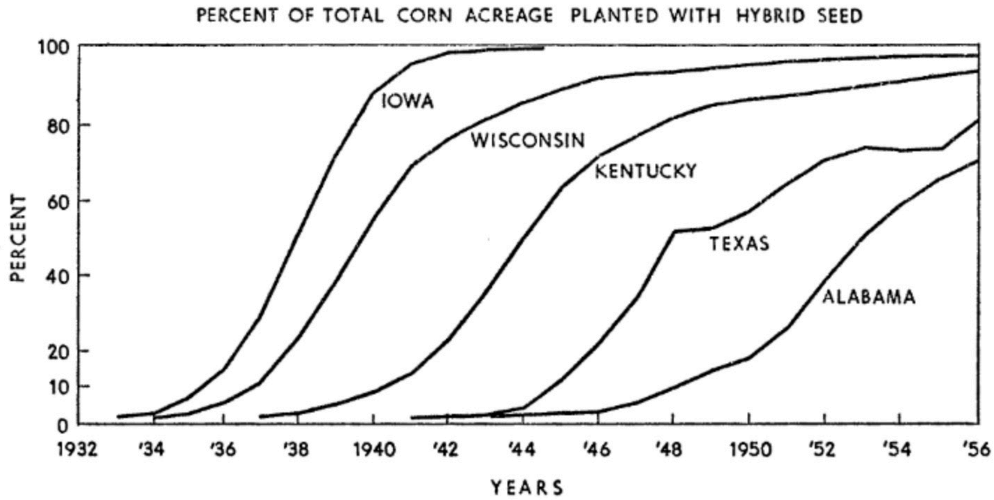

Figure 2.12: Adoption rate of hybrid corn across states in the US.
Source: Griliches (1957)

These include not only technological refinements but also more effective policy frameworks, market structures, and deployment strategies. For instance, Marchetti (1983) demonstrated that Japan, despite being a late adopter of automobiles, experienced faster growth rates than the U.S., once adoption began. This same logic asserts that learning is not purely local but can be accelerated through the global circulation of knowledge, technology, and capital. Grubler (1996) extends this argument but cautions that although technologies may grow quickly in recipient contexts, they do not reach the same absolute levels or density as in the core. See also Wilson and Grubler (2011); Wilson et al. (2013). For example, Russia's railway network, while expanding rapidly, never matched the coverage or integration seen in the UK.

The second position emerges from the unfavourable conditions view, where **contextual disadvantages dominate**. It underscores the role of structural constraints — such as weak institutions, limited financial resources, and poor access to global knowledge networks — in delaying both adoption and scaling. From this position, context outweighs learning. Griliches (1957) foundational work on hybrid corn, for instance, found that U.S. states with more favourable agro-economic conditions adopted the crop more rapidly, while the speed of adoption in late-adopters lagged. See Figure 2.12. Dixon (1980) later reinforced this argument, showing that late adopters not only began later but also exhibited slower growth rates. At a global level, Comin and Hobijn (2004) further supported this perspective by documenting how developing countries consistently adopt a wide range of technologies more slowly and later than wealthier nations — regardless of sector. Their findings suggest that deep-rooted structural barriers inhibit not only the timing of adoption but also the capacity to scale up technologies, even in the presence of global technological learning.

The third position is the **balancing effect view**, articulated by Cherp et al. (2021), which argues that the positives of learning from early adopters and negatives of contextual constraints in late adopters cancel each other out. This dynamic interaction results in similar overall growth rates between early and late adopters. Similar to this view, Dekimpe et al. (1998) found no consistent relationship between the timing of adoption and the speed at which mobile phones spread across 184 countries.

Arbitrating between these perspectives is important because each implies a distinct approach to policy intervention in late-adopting regions. For example, if accelerated adoption depends primarily on learning spillovers, policies should focus on facilitating access to knowledge, technology, and best practices from early-adopting regions. If structural and contextual barriers dominate, policy must directly address local constraints in these regions. Even in scenarios where these forces balance each other out, interventions must both leverage learning and mitigate local disadvantages to prevent persistent spatial disparities. Understanding which dynamic is influential is therefore critical, as it determines whether policy can accelerate adoption effectively, promote equitable regional development, and avoid reinforcing pre-existing inequalities in technological and infrastructural development.

2.5 Knowledge gap

In the Figure 2.13 and Table 2.1, I position this dissertation within the broader literature landscape and summarise the knowledge gap and main contributions, respectively.

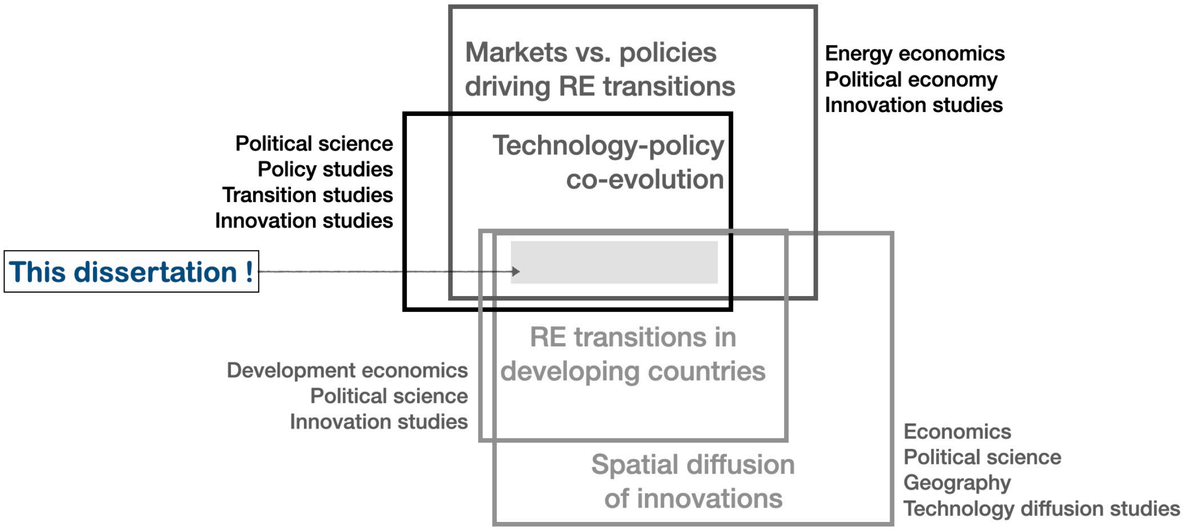

Figure 2.13: Positioning this dissertation within the broader literature landscape.

Literature cluster	Puzzles and knowledge gaps	Research questions
Markets vs Policies in Driving RE Transitions	As technology costs decline, there is an ongoing debate: Do markets alone sustain momentum, or does policies remain essential due to emerging barriers?	RQ1 : What is the relative role of costs and policies in accelerating solar growth over time in India?
Technology - Policy Co-evolution	The literature acknowledges that technology and policies co-evolve with feedbacks originating from multiple sources. However, empirical evidence for such studies remains fragmented and mostly qualitative case-based in developed countries.	RQ2 : How do policies change over time as solar deployment increases in India?
RE Transition in Developing Countries	A core debate centers on whether developing countries can leapfrog to cleaner technologies faster than frontrunners by using developed countries' experience and innovations. This relates to the wider debate on whether later-adopting regions can catch-up and converge with early adopters.	RQ3 : What is the relative role of policies in accelerating solar growth in India, a technology-recipient country?
Spatial Patterns in Technology Growth	The literature explores why technology adoption varies spatially, including effects of policies. However, the role of national policies in either reducing or increasing spatial inequalities in technology adoption, sub-nationally, is unclear.	RQ4 : How do policies change over space with increasing solar deployment in India, sub-nationally? Do they enable late-adopters to catch up?

Table 2.1: Literature gap and the four corresponding research questions addressed in this dissertation.

3. Theory and Methods

This chapter is divided into two main parts: Section 3.1 presents the philosophical and conceptual framing. Section 3.2 details the analytical and methodological approach. It is broadly organised around the key pillars of the conceptual framework. Finally, Section 3.3, provides a graphical summary of the research design, setting the stage for the empirical chapters that follow.

3.1 Conceptual framing

I outline my conceptual framing in three parts. First, I ground my philosophical position in critical realism. This provides the ontological and epistemological basis for employing the three-perspective framework to study national energy transitions. Next, I unpack the key aspects of the framework, focusing on two features most relevant to my approach. Finally, I explain how these features are conceptually operationalised, using insights from across disciplines.

3.1.1 A critical realist lens

A research philosophy includes three things: ontology, which concerns the nature of reality and what exists; epistemology, which addresses how we come to know what exists and what sources of knowledge are considered valid; and methodology, which refers to the scientific approaches deemed appropriate for acquiring that knowledge (Grix 2002). My research design is grounded in the philosophical assumptions of critical realism, first introduced by Roy Bhaskar in A Realist Theory of Science (Bhaskar 1975).

Critical realism occupies a middle ground between positivism and interpretivism (Sorrell 2018). While interpretivism emphasises the subjective construction of reality, critical realism asserts that reality exists independently of our perceptions, even though our understanding of it is socially produced, historically contingent, and shaped by individual subjectivity (Bhaskar 1975; Sorrell 2018). In this regard, critical realism shares with positivism the assumption of a single, objective reality. However, it diverges from positivism by rejecting the notion that social phenomena can be fully explained through observable regularities alone. Instead, critical realism views scientific inquiry as an ongoing, iterative process aimed at approximating truth (Bhaskar 1975; Sorrell 2018). It differentiates reality into three domains: the empirical (events experienced or observed), the actual (events that occur, whether observed or not), and the real (underlying mechanisms or structures that generate observable outcomes). This layered understanding of reality enables researchers to move beyond surface-level observations to uncover the deeper, often hidden causal mechanisms at work (Bhaskar 1975). From this perspective, the aim of science is not merely to predict or interpret phenomena, but to explain how, why, and under what conditions specific social outcomes occur (Elder-Vass 2010; Sayer 2000; Sorrell 2018).

There is, albeit limited, a body of research (explicitly) applying a critical realist lens to the study of energy transitions. Notably, Geels' Multi-Level Perspective (MLP) builds on the philosophy, offering a framework to analyse how transitions result from interactions within and between niches, socio-technical regimes, and the broader landscape (Geels 2002, 2022). However, critics have argued that the MLP does not fully adhere to critical realist tenets, citing its vague conceptualisation of social structures and rules, its tendency to use the framework more as a rough idea than an explanatory model, its reliance on narrative case studies, and its broad theoretical scope (Sorrell 2018). Yet, they have not dismissed the relevance of critical realism in studying energy transitions. Rather, Sorrell argues critical realism's emphasis on understanding the underlying causal mechanisms, structures, and powers that produce observed social outcomes continues to make it a valuable approach for studying complex, multi-dimensional phenomena, like energy transitions (Sorrell 2018). Building on this foundation, Cherp et al. (2018) introduced the three-perspectives meta-theoretical framework for studying national energy transitions. Their goal has been to advance a mechanistic understanding of reality, enabling explanations that go beyond surface-level patterns to explore deeper causal processes. This meta-theoretical framework forms the conceptual backbone of the research design.

3.1.2 The three perspectives of national energy transitions

Cherp et al. (2018) observe that energy transitions involve interactions between economic development, technological innovations, and policy change. They propose a conceptual framework that integrates the techno-economic, socio-technical, and political perspectives of studying national energy transitions. The framework includes a few key features. One, it identifies the three perspectives as analytical lenses for studying transitions. Two, it develops a conceptual model that allows mapping key variables and theories representing systems within each perspective. Three, it highlights the idea of co-evolution within and across the systems within the three perspectives. Four, it introduces the idea of "fits and misfits" to show when one perspective/ group of perspectives might explain a transition episode better than others, allowing the *perspectives* an explanatory power. Finally, it acknowledges that perspectives' explanatory power can vary across contexts. In sum, the framework provides a rationale for adopting an interdisciplinary approach that moves beyond a singular view when explaining national energy transitions. While all aspects of the framework are interwoven throughout this dissertation, my conceptual framework is primarily built around two features. One, the identification of key variables and theories to look through the three perspectives. Two, incorporating the concept of co-evolution within and among systems studied under the three perspectives.

According to Cherp et al. (2018), the techno-economic perspective includes energy flows, infrastructure, and markets. The perspective draws on domains of economics and engineering, and emphasises mechanisms such as supply, demand, and price signals. This lens is typically applied in major energy modelling practices today (Beek et al. 2020). However, studies within this domain often treat policy change as exogenous (Jewell and Cherp 2023). The socio-technical perspective views technological change as shaped by social context. Rooted in sociology and evolutionary economics, it highlights concepts such as innovation systems, technological learning, creation of niches, and the MLP (Bergek et al. 2008; Geels et al. 2016). While this approach captures how new technologies emerge and spread, it often pays less attention to deeper political and economic structures (Grubb et al. 2015; Meadowcroft 2009). Finally, the political perspective centres around politics, institutions, and policies. It draws from political science and public policy, and focuses on how political interests and institutional capacities shape change. However, this perspective often overlooks the practical and material constraints posed by technologies and infrastructure.

The idea of co-evolution in this theoretical framework builds on works from Perez (2002) and Foxon (2011), and includes three main points. One, systems under each perspective evolve along their own path to some extent, or they are semi-autonomous. For example, innovations grow and diffuse in certain ways irrespective of policy (Wright 1936), or policies change in certain ways irrespective of technological innovation (Hall 1993). Two, systems studied within each perspective influence one another. For example, a policy incentive, such as a subsidy (political) for solar modules, might accelerate the deployment of solar PV (socio-technical), which in turn reduces module costs (techno-economic) and supports further policy action (political). While these cross-perspective feedbacks can be positive, unlocking momentum in another system (Nijsse et al. 2023; Pahle et al. 2018), it can also be negative. For example, conflicts over land-use and acceptance (socio-technical) can limit policy support towards renewables like solar and wind (political), which can increase their costs (techno-economic) and stall adoption (Frantál et al. 2023). Three, the relative influence of each perspective can shift over time

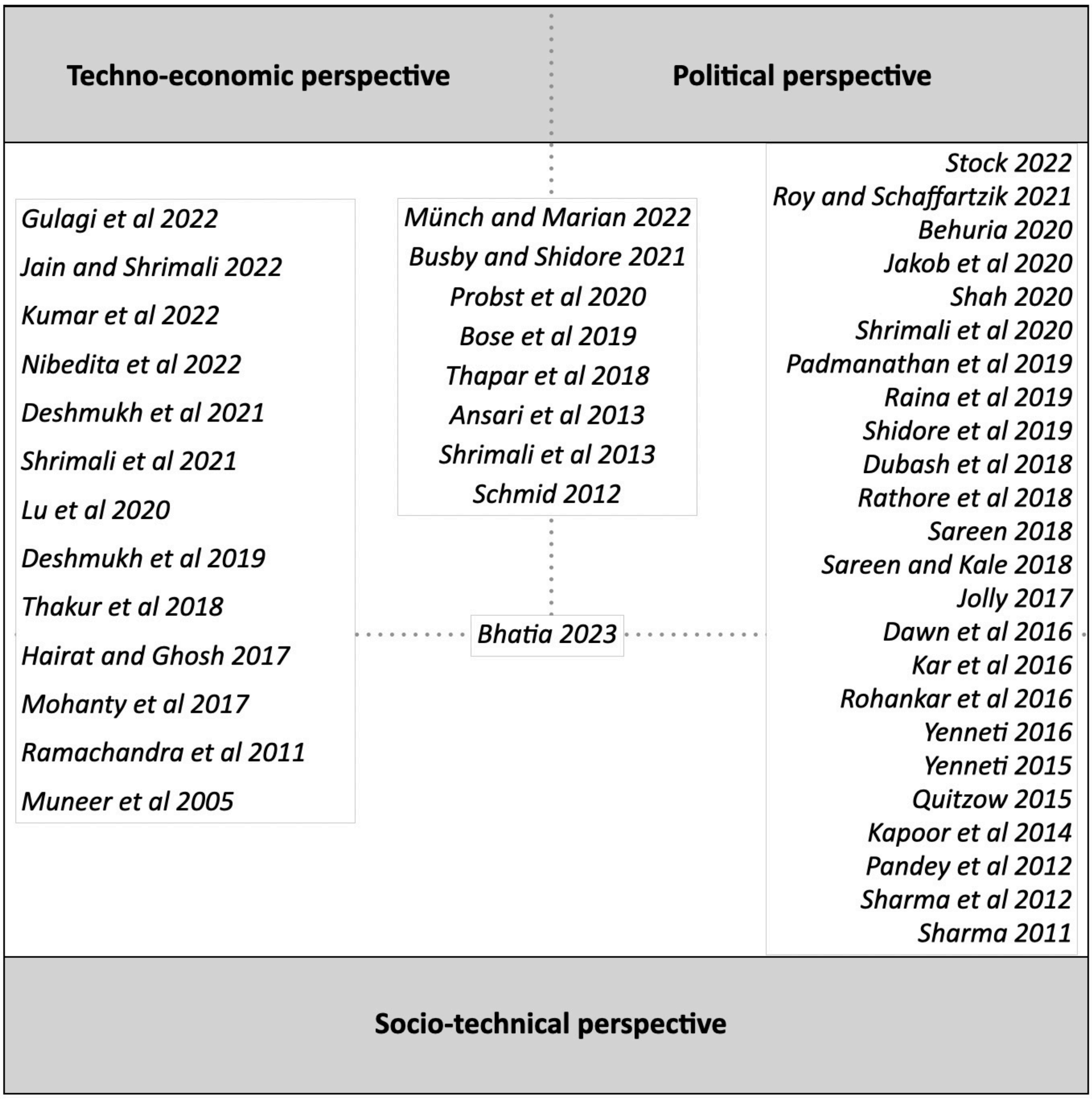

Figure 3.1: Studies on solar in India grouped under the three-perspectives framework. *Literature identified can be grouped into four clusters: (i) those at the intersection of techno-economic and socio-technical perspectives, examining the relative role of economic factors in driving solar growth and vice versa; (ii) those at the intersection of the political and socio-technical perspectives focusing on the relative role of political and policy factors driving solar growth and vice versa; (iii) those at the intersection of techno-economic and the political perspectives linking changing economics to policy shifts and vice versa; and (iv) those incorporating all three perspectives. Sources include (Ansari et al. 2013; Behuria 2020; Bhatia 2023; Bose and Sarkar 2019; Busby and Shidore 2021; Dawn et al. 2016; Deshmukh et al. 2021, 2019; Dubash et al. 2018; Gulagi et al. 2022; Hairat and Ghosh 2017; Jain and Shrimali 2022; Jakob et al. 2020; Jolly 2017; Kapoor et al. 2014; Kar et al. 2016; Kumar et al. 2022; Lu et al. 2020; Mohanty et al. 2017; Muneer et al. 2005; Münch and Marian 2022; Nibedita and Irfan 2022; Padmanathan et al. 2019; Pandey et al. 2012; Probst et al. 2020; Quitzow 2015a; Raina and Sinha 2019; Ramachandra et al. 2011; Rathore et al. 2018; Rohankar et al. 2016; Roy and AnkeSchaffartzik 2021; Sareen 2018; Sareen and Kale 2018; Schmid 2012; Shah 2020; Sharma 2011; Sharma et al. 2012; Shidore and Busby 2019; Shrimali 2021; Shrimali et al. 2020, 2013; Stock 2022; Thakur et al. 2018; Thapar et al. 2018; Yenneti 2016; Yenneti and Day 2015).*

or along the phases of technology growth, with no single perspective leading throughout. For example, (Vinichenko 2018) (p. 72) captures how different phases of technology growth are shaped by a specific configuration of mechanisms operating under the three perspectives.

Work integrating the three perspectives in studying utility-scale solar PV growth in India remains limited. Figure 3.1 categorises the existing literature by the theoretical lens they adopt. An exception is Bhatia (2023), who provides a narrative review of studies published between January 2011 and October 2023, offering a useful foundation for understanding the state of knowledge. However, its scope remains constrained by several factors: the restricted time frame; the absence of empirical quantification; limited analysis of the roles of public and private actors; no clear distinction between cost and policy drivers; and a lack of systematic mapping of either the historical diffusion of solar PV or future technology development pathways. In this dissertation, I address these limitations and integrate the three perspectives framework targeted specifically to understand the relative role of costs and policies in accelerating RE growth in a developing country context.

3.1.3 The conceptual framework

Figure 3.2 provides a visual illustration of the conceptual framework. Using Cherp et al's meta-theoretical framework, I conceptualise utility-scale solar growth in India as an outcome of co-evolution across systems within the techno-economic, socio-technical, and political perspectives.

Under **the socio-technical perspective**, I study solar growth as a temporal and spatial process. I draw on theories of diffusion of innovations, specifically works relating to phases of technology growth and spatial dimensions of technology adoption over time (as discussed in Section 2.2.2 and 2.4). Growth is viewed as a social outcome, influenced by factors like technological learning and regional contexts shaped by institutional and regulatory contexts (Geels 2004).

For example, solar growth can be hindered when they are incompatible with dominant regimes, facing backlash from fossil fuel companies (Breetz et al. 2018) or resistance due to land-use conflicts (Frantál et al. 2023). Conversely, solar growth can be supported when the regional resource potential is high, and or when the incumbent regime is not as strong (Schmidt and Sewerin 2017). At the same time, when solar growth matures, it may also reshape existing social configurations (Kuzemko et al. 2016). For example, as solar grows more widely, increasing profitability may influence fossil fuel-based power utilities to shift towards or simply diversify by incorporating renewables into their portfolios. However, increasing the profitability of the industry may also trigger contestation across niche vs incumbent industries. While the former will reinforce technological learning and drive further growth, the latter may lead to political contestation that is asynchronous with technological growth. I embed these co-evolving interactions by looking at **technology** adoption over time and space, shaped by the actions of two types of dominant **social actors**[11] within the Indian solar landscape. The actors include: public enterprises, such as state-run power distribution companies (DISCOMs), and private businesses, including solar developers and groups in the solar supply chain (e.g., solar manufacturers).

Under **the techno-economic perspective**, I examine the co-evolution of absolute and relative solar PV costs, drawing on theories of technology learning and cost decline. I trace how cost-competitiveness shifts with solar's growth, situating this within an electricity market that is only partially liberalised[12]. I adopt a dynamic interpretation of costs and competitiveness — varying not only over time but also across the social actors involved[13]. Following Christophers (2024) (p. 133–164), my focus is not on measuring profitability per se, but on how techno-economic conditions differ over time and vary for solar project developers and the buyers of solar electricity. For example, for developers, competitiveness may hinge on the margin be-

[11]Social actors here are technical actors directly involved in the solar industry within the limits of the wholesale electricity market.

[12]On electricity market liberalisation, seeUrpelainen and Yang (2019)

[13]Further discussed in Section3.2.2.

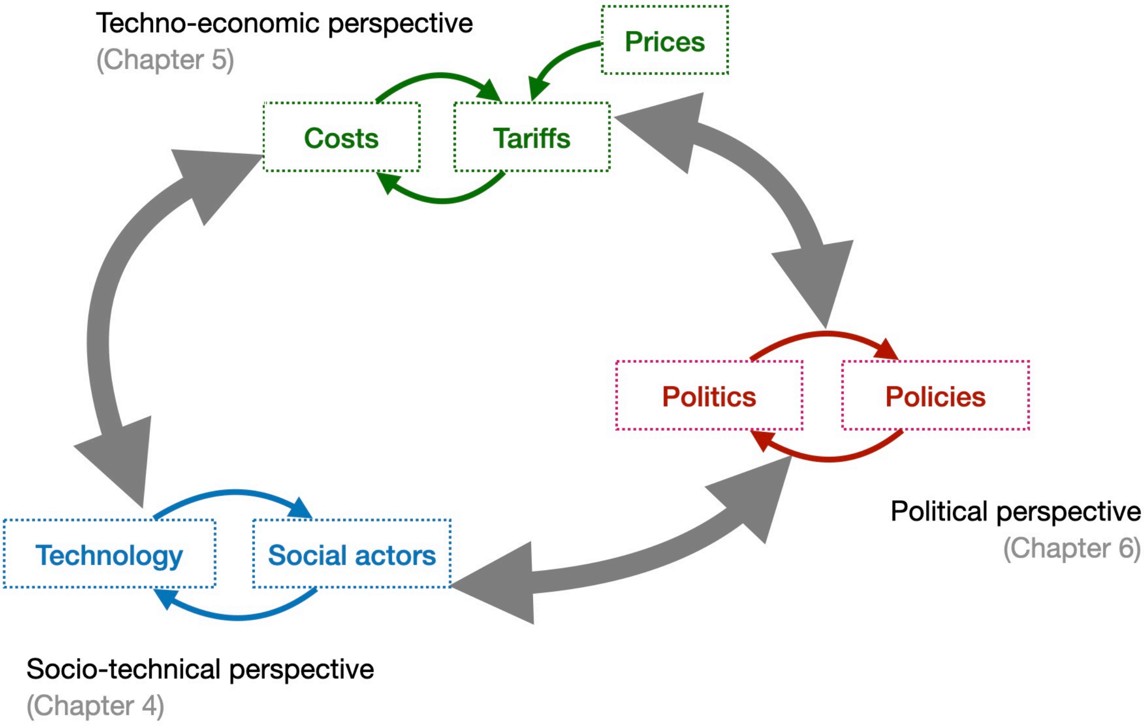

Figure 3.2: The conceptual framework of this dissertation

tween production costs and selling prices; for utilities, it may depend on how solar compares to alternative energy sources for meeting electricity demand reliably. These assessments can also shift over time. In early growth stages, developers may benefit from first-mover advantages and policy support, while utilities may face losses from stranded assets and high procurement costs. Later, declining technology costs may compress developer margins, while utilities benefit from lower procurement prices. In other words, techno-economic developments may change socio-technical configurations that bear political implications. I embed these co-evolving interactions by looking at the evolution of the **cost** of producing electricity (for solar developers) and the **tariffs** of selling and buying solar electricity (for solar developers and power procurers, respectively), relative to the **prices** of selling and buying electricity overall (from other energy sources) at the wholesale level.

Under **the political perspective**, I study the co-evolving dynamics of political and policy change. I draw broadly on theories of vested interests and institutional capacity, on the one hand, and theories of policy change, on the other. Interests are understood through a state-structured approach, where they emerge from political contestation and negotiated compromises among social actor groups (Jacobsson and Lauber 2006). However, the realisation of these interests depends on social actors' capacities, which shape the institutional context (Geels 2014). For example, interests may be economic and political, including climate change mitigation, energy security, and economic growth for policymakers(Ollier et al. 2020); profitability and access to capital for solar developers (Steffen et al. 2022); and concerns regarding grid stability and supply-demand balancing for power utilities (Christophers 2024). Institutional capacities, meanwhile, may be shaped by the structure of the political system, access to decision-making processes, policy enforcement, and administrative reach, or the ability to mobilise resources and shape dominant narratives (Edmondson et al. 2019). Against this, policy change is seen to emerge as a non-linear and cumulative process, influenced by multiple interacting factors rather than a simple trajectory of drivers and barriers[14].

Plus, moments of disruption external to the innovation process may play a critical role (Aklin and Urpelainen 2013; Schaffer and Bernauer 2014). In other words, while policies may evolve as a result of competing interests and shifting policy paradigms, they may also coincide with external changes that open or close windows of opportunity for actors that influence policymaking (Kern and Rogge 2016). For example, the dramatic cost decline of solar technologies globally may shape domestic policies by encouraging further support towards solar (Schmidt and Sewerin 2017). At the same time, policy decisions targeting support for solar foreclose support for alternative technologies (Schmidt et al. 2016), setting a path for future socio-technical, techno-economic, and political developments. Therefore, under this perspective, I look at the interactions between politics and policies. Here, **politics** is seen as the process through which interests, institutions, and ideas evolve and prevail, while **policies** are seen as an outcome of politics (Meadowcroft 2011).

[14]Discussed in the technology policy evolution literature Section 2.2)

3.2 Analytical approach and methods

Aligning with the conceptual framework, I conduct a within-case comparative study focusing on utility-scale solar PV in India. My overall approach is that I look at the relative role of systems within the techno-economic and the political perspectives in influencing changes in systems studied within the socio-technical perspective.

The temporal scope of my analysis spans 20 years from 2004 to 2024, with specific chapters zooming in on shorter time frames depending on data availability during the time of analysis. For example, the techno-economic analysis (in Chapter 5) focuses on the years 2010-2023, while the socio-technical and political analysis (in Chapters 4 and 6) considers the full two decades. Within the spatial scope, I include both national and state-level findings. In most cases, expect national vs state policy efforts, national trends are derived by aggregating state-level developments. I look at 18 Indian states, grouped into three broad regions. The **North-west** includes Haryana, Gujarat, Madhya Pradesh, Punjab, Rajasthan, and Uttarakhand. The **North-east** includes Assam, Bihar, Chhattisgarh, Odisha, Uttar Pradesh, Uttarakhand, and West Bengal. The **South** includes Andhra Pradesh, Karnataka, Kerala, Maharashtra, Tamil Nadu, and Telangana. See Figure 3.3. Each state has more than 100 MW of installed utility-scale capacity (as of December 2024) and together accounts for around 75 MW or nearly 100% of India's total installed capacity in this segment (MNRE 2025d).

The sectoral focus is on electricity up to the wholesale level. See Figure 5.1. This is because solar is primarily used for electricity generation, and features at the retail level (including pricing, supplier choices, and public participation) remain limited and highly regulated (Chattopadhyay et al. 2023). My overarching analytical approach is a mixed-methods research design. On the quantitative side, I use technology growth models, techno-economic analysis, and policy effort metrics to track the co-evolution of systems under each of the three perspectives. On the qualitative side, I use process tracing to explain the co-evolution of systems across perspectives.

This combination allows preserving the generalisability of quantitative analysis and the depth of qualitative insights (Sovacool et al. 2018).

3.2.1 Measuring solar growth over time and space (Chapter 4)

To measure solar growth over time and space, I draw on approaches from the long-standing body of technology diffusion research. I examine how solar has expanded over time in India, resulting from shifting contributions across different states. While doing so, I also highlight the present status of growth within each state and the outstanding solar potential remaining in them. The methods in this section adhere to the analysis in Chapter 4, which zooms in through the socio-technical lens.

Phases of technology growth

One popular way of measuring the phases of technology growth is through the use of a logistic growth function, which models diffusion as an S-curve defined by three parameters: the timing of take-off, the speed of growth (rate), and the market's maximum potential (or the saturation level) (Wilson 2012). This approach captures early slow growth, rapid acceleration, and eventual saturation. However, as discussed in Section 2.2.2, growth of RE technologies goes through four (and not three) phases: (i) a formative phase with low and erratic growth, (ii) an acceleration phase with exponential growth where each year more capacity is added, (iii) a prolonged stable growth phase marked by pulsating growth but a consistent or linear pattern overall, where each year on average similar capacity is added, and (iv) a stalling phase where growth slows or plateaus (Jewell et al. 2025).

To identify these phases at both national and state levels, first, I determine the year of take-off, defined as the year solar electricity reaches 0.5% of total electricity generation in a state or nationally Vinichenko (2018). This marks the shift from the formative to the acceleration phase. Then, I fit annual cumulative installation data to four types of growth models: Exponential,

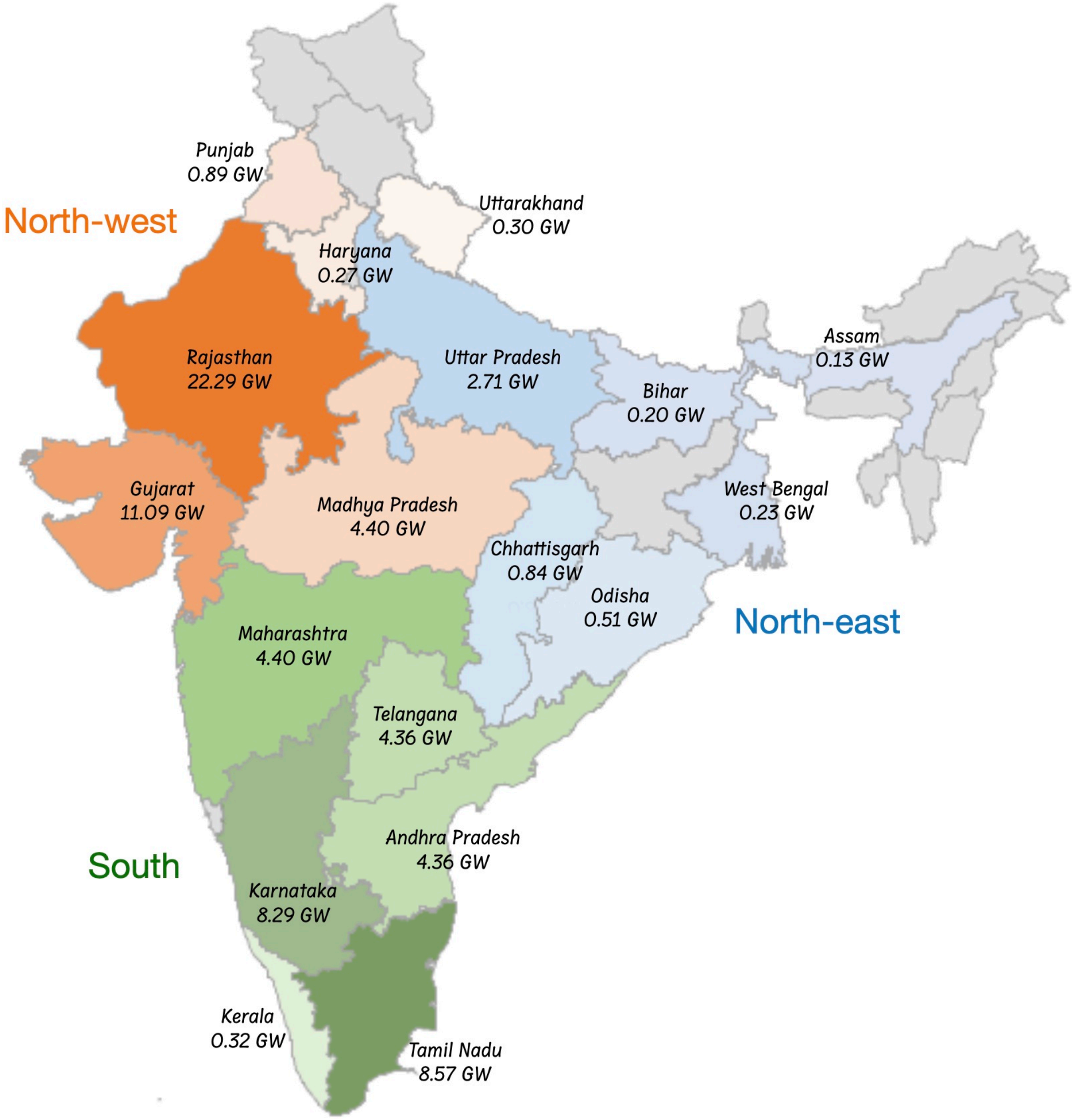

Figure 3.3: Selected Indian states and regional grouping.
The figure shows the installed capacity as of December 2024 in the 18 selected Indian states grouped into 3 separate regions. The north-western states are in orange. Southern states are in green. North-eastern states are in blue. This colour scheme for states is maintained throughout the dissertation. Darkness of a colour represents the scale of total deployment.

Logistic-Linear, Linear, and Gompertz, based on methods developed by Vinichenko (2018). The best-fitting models were the Logistic-Linear and Gompertz models. I classify the current growth phase based on the average maturity (Cherp et al. 2021) from these two model outputs. Less than 50% maturity equals the Acceleration phase, and more than 50% maturity equals the stable or stalling phase. I do not differentiate between the Stable and Stalling phase, as solar in India is still relatively new, and there is little ground to meaningfully disregard a re-acceleration in stalling states. However, from the graphical illustration, it is possible to distinguish between cases of stable and stalling growth (See Figure 4.2).

I use three main input variables: (i) annual installation data from MNRE (2025d) physical achievements database; (ii) solar electricity generation data from the Indian Climate and Energy Dashboard (MNRE 2025d); and (iii) total electricity generation, also from ICED 2024. Since solar generation data is only available from 2015 onward, I estimate generation for earlier years using an average capacity utilisation factor (CUF). This is calculated using years where both installed capacity and generation data are available, using the formula:

$$\mathrm{CUF}_t = \frac{\mathrm{Generation}_t}{\mathrm{Installed\ Capacity}_t \times 8760} \times 100. \tag{3.1}$$

Spatial patterns of technology growth

To understand how solar grows or can grow in India, it is important to understand how growth unfolds within India, across different states and regions, and what factors drive it. Equally important is understanding how long these drivers can be sustained, and the extent to which they can be adapted or maneuvered within existing contextual constraints. To explore these patterns, I take a three-part approach. First, I account for annual solar installations across Indian states over time, using figures published by the Ministry of New and Renewable Energy (MNRE 2025d). By observing when and where significant growth occurred, I assess how state-level trends shaped the national trajectory.

Second, I conduct a brief literature review to assess what is already known about the drivers of these spatial patterns. This review includes literatures in Figure 3.1, but particularly zooms in on nine peer-reviewed articles and two master's theses, including my own. See Table 4.1. Most of this body of work focused on early patterns of solar growth and was conducted in the years leading up to 2022, India's first solar target year. These studies employ a wide range of methods. Some use qualitative, case-based approaches to examine state differences through path dependency and institutional capacity (e.g., Jolly (2017); Sareen (2018); Sareen and Kale (2018)), while others rely on quantitative methods such as regressions and econometric models covering most, if not all, states (e.g., Jakhmola (2021); Shrimali et al. (2020); Thapar et al. (2018)). Mixed-method approaches also feature in this literature (e.g., Bhowmik (2020); Busby and Shidore (2021)).

These studies also differ in what they measure. Most use deployment levels as the main dependent variable, though some also examine related aspects like solar auctions (Thapar et al. 2018) and the timing of solar adoption or "take-off" (Jakhmola 2021). The greatest variation lies in the independent variables included. These range from geographical factors (e.g., solar radiation, land suitability, availability of competing energy sources like coal), to political factors (e.g., ruling party affiliation, specific policy adoptions), to economic indicators (e.g., state GDP, electricity demand, consumer base, profitability), as well as social and institutional factors (e.g., presence of farmers' movements, financial health of distribution companies). Despite these differences, the goal of this review is to identify common findings and narratives across the literature, particularly how contextual factors, besides costs and policy developments, shape solar growth.

The third part of this analysis focuses on understanding how solar could grow in the future. To answer, I adopt a two-part approach. First, I look at past growth rates. The diffusion literature generally presents three main positions: (i) late adopters may grow faster than early adopters by learning from their experiences, but may not reach the same cumulative scale; (ii) late adopters grow more slowly and never catch up to early adopters; and (iii) the growth rates of early and late adopters remain broadly similar[15]. I contribute to this debate from a sub-national context. Using annual cumulative solar installation data published by MNRE (2025a), I calculate the peak growth rate for each state by calculating three-year and five-year moving averages. Then I compare growth rates to the take-off year.

I also assess the remaining potential[16] for future solar growth across different states and regions based on the total solar potential of each state (MNRE 2025a). The goal here is to understand how much room is left for expansion, considering the diverse geographies and levels of current development. This is because: (i) while national-level solar growth is the aggregate result of state-level dynamics, the contribution of individual states may vary over time; and (ii) geophysical characteristics[17] will impose physical limits on how far costs and policies can push solar expansion.

3.2.2 Measuring cost and cost-competitiveness (Chapter 5)

Based on the literature discussed in Section 2.1.1, I interpret solar costs in two ways. One, absolute cost, referring to the total cost of producing electricity from solar over its lifetime. This is measured by the levelised cost of electricity (LCOE), which incorporates capital expenditure, operational and maintenance expenditures, and financing costs (IEA 2011). The second is relative cost, which, among other things[18], compares the solar LCOE with the cost of electricity from conventional energy sources or other electricity prices (IEA 2011). In other words, while absolute cost indicates how much it costs to build a new solar project, relative cost indicates whether or how well a new solar project can compete in the market and generate profit. This notion of relative cost underpins the concept of grid parity. In this context, LCOE serves as

[15] For more elaborate discussion refer to Section2.4.2

[16] Solar potential might change (see table 3.1 in MNRE (2025a)) based on technological improvements, policy interventions, and social favourability. Yet, in the last 10 years of publishing similar reports, this hasn't. On the policy-making level, India's solar potential appears to be a constant assumption, so far.

[17] Here, including solar irradiance and land availability.

[18] Relative cost has also been calculated based on manufacturing costs, balance of system costs, retail and wholesale electricity prices (Yan et al. 2019; Yang 2010).

a proxy for technology learning (following Wright (1936)) while grid parity marks a point on the evolving cost, or technology learning curve. The grid parity point is popularly seen as the "holy grail" (Munoz et al. 2014), or "chasm" (Yang 2010), or positive "tipping point" (Nijsse et al. 2023; Wang et al. 2025), after which technology growth accelerates. In other words, while declining costs itself is a sign of increased competitiveness, grid parity signals a specific level of this competitiveness. The methods in this section adhere to the analysis in Chapter 5, which zooms in through the techno-economic lens.

Measuring cost

LCOE is defined as the present value of the total cost of generating solar electricity over a project's lifetime (Aldersey-Williams and Rubert 2019; Timilsina 2020). It can also be defined as the price at which solar electricity must be sold to breakeven by the project's end, while earning a return on investment equal to the cost of capital (NREL 2024). LCOE is calculated based on the formula (Egli et al. 2023):

$$\text{LCOE} = \frac{(\text{CAPEX} \times \text{CRF}) + \text{OPEX}}{\text{CUF} \times 8760}, \tag{3.2}$$

where CAPEX denotes the total installation cost, OPEX includes operations and maintenance expenses, and CUF is the capacity utilisation factor. The capital recovery factor (CRF) is determined by:

$$\text{CRF} = \frac{\text{CoC} \times (1+\text{CoC})^T}{(1+\text{CoC})^T - 1}, \tag{3.3}$$

where CoC is the cost of capital and T is the project lifetime, assumed to be 25 years MNRE (2017). All cost data range from 2010-2023 and are sourced from IRENA (2024a). Values are in 2023 USD. Due to a lack of detailed and consistent component cost data at the state level, I assume that CAPEX, OPEX, and CoC are uniform across all Indian states. However, location-specific variation is retained by incorporating the actual calculated capacity utilisation factor (CUF) for solar power plants, using methods outlined in the previous section. See Table 3.1

for all input variables to calculate LCOE. National level LCOE is the weighted average LCOE from the 18 states studied, with weights assigned based on annual capacity additions.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
CAPEX ($/kw)	5875	3620	3176	3269	2218	1512	1301	1298	922	719	685	654	664	711
OPEX ($/kw)	26	24	18	15	14	12	11	11	10	10	10	10	9	9
WACC (%)	10	9.2	11.5	8.10	12.60	11.60	10.40	8.30	11	9.20	7.5	5.9	5.9	8.41
Project lifetime	25	25	25	25	25	25	25	25	25	25	25	25	25	25

	AP	AS	BI	CH	GU	HA	KA	KE	MP	MH	OD	PU	RA	TN	TE	UP	UT	WB
CUF (%)	19	8	15	14	16	17	18	23	14	14	20	22	20	16	18	16	12	6

Table 3.1: Inputs for calculating Levelised Cost of Electricity.
The table shows the input values for calculating LCOECal across states. CUF values are based on own calculations using equation 3.1. Cost data is from IRENA (2024a).

The calculated LCOE (LCOECal) reflects the actual techno-economic cost of generating solar electricity without accounting for policy support[19]. For instance, while developers may be compensated based on a 17% CUF even during curtailment (Rustagi and Chadha 2020), that cost is borne by the government, which is captured in the LCOE here. Previously, studies have equated the cost of producing solar electricity with solar auction tariffs (AT)[20], calling it the ”financial LCOE”, which incorporates policy support (Egli et al. 2023). Here, I make this distinction between the cost of producing solar electricity (LCOE) and the price at which it is sold (the auction tariff or AT). An attempt was made to account for financial support in LCOE calculations by including central financial assistance as capital subsidies provided to states by the national government between 2012-2022[21]. However, incorporating these had no significant impact on LCOECal (see Figures A.2 and A.3 in Appendix), so they were ultimately not included in the analysis. Yet, it remains an important observation.

[19]This approach is similar to how IRENA measures LCOE. See cost methodology in IRENA (2024a).

[20]Auction tariffs are the prices at which solar capacity is contracted by off-takers, such as state distribution companies, through solar auctions. These ultimately translate the price that developers receive for selling the electricity generated from solar projects.

[21]These funds did not distinguish between grid-connected and off-grid, or between utility-scale and rooftop projects. Given the dominance of utility-scale projects during this period, I assumed that most of the support went to solar.

Another observation concerns the treatment of land costs. I have relied on IRENA's cost estimates, which include land costs within OPEX. However, a comparison with the assumptions used in Wang et al. (2023) to calculate LCOE for solar energy in China indicates that IRENA underestimates land-related expenses (see the comparative Table A.1 and Figure A.5 in the Appendix). Due to the lack of consistent and transparent data, especially at the state level, and significant variation in land acquisition or leasing practices, land costs were also not explicitly included in the LCOECal. Nevertheless, this remains an area for future investigation. Preliminary data collected from the Land Conflict Watch Database (LCW 2024) suggest that most solar projects in India are located on rural private or common lands, with land typically leased rather than acquired. In the case of solar parks, land is acquired by state governments and leased to developers. Available compensation data is limited, but land acquisition costs generally range from 12–30 USD/kW[22]. In Karnataka, for example, lease rates ranged between 1–2 USD/kW per year, escalating by 5% every two years over 28 years, amounting to 35–70 USD/kW over 25 years (LCW 2025). In comparison, estimated land costs in China range from 47–310 USD/kW based on the type of land cover (Wang et al. 2023). A sensitivity analysis shows that a ±25% change in land cost leads to a ±7% change in LCOE (see Figure A.4 in Appendix). While not the dominant factor, land costs remain significant, especially considering the potential underestimation in popular assumptions and the likelihood of changing land costs with technology growth (whether due to increasing demand and/or changing social acceptance).

Measuring cost-competitiveness

I measure cost-competitiveness drawing from the concept of grid parity. There are different definitions of grid parity, yet the core idea is straightforward. It refers to the point at which the cost of generating electricity from a new source, here solar, is equal to or falls below the cost of generating electricity from existing sources (Munoz et al. 2014). However, the concept has been widely criticised for being overly simplistic to inform industry or policy decisions –

[22] Based on the Land Conflict Watch Database. As of February 2024.

especially within the context of liberalised electricity markets, where it has also been primarily studied (Munoz et al. 2014). The main disagreement lies in how parity should be calculated, or which costs and prices should be compared. For example, Olson and Jones (2012) would argue that solar LCOE should be compared to the marginal cost of conventional electricity production rather than its lifetime costs, since much of the investment in conventional generation is already sunk. Additionally, the quality or the "value" of the two types of electricity should be considered, given the variability and intermittency of solar (Choi et al. 2015; Olson and Jones 2012; Wang et al. 2025). Some argue that grid parity is a "moving target," shaped by factors such as time-of-use pricing and broader market volatility (Bhandari and Stadler 2009; Lund 2011; Olson and Jones 2012).

Munoz et al. (2014) also notes that there is no single point of grid parity. Rather, there are multiple types that emerge along the cost curve. This is because the electricity market is a hub of different actor groups – retail consumers, utilities, wholesale suppliers – each operating under different pricing structures and business models (Wang et al. 2025) (Fig3). Also in Christophers (2024). For instance, the SolarPower Europe[23] predicted that retail grid parity in countries like Spain, Italy, and Germany would occur between 2012 and 2015, while wholesale parity might not be achieved until around 2030 (Munoz et al. 2014). Plus, there are geographic variations (Breyer and Gerlach 2013). This may be due to resource availability, which is likely to affect production costs and electricity pricing, both for renewables and conventional energy sources. As a result, even within a single country, certain regions may reach specific types of parity at different points in time (Yan et al. 2019). Thus, rather than a single tipping point, grid parity is better understood as a gradual, uneven process, shaped by time, geography, market conditions, and from the perspective of a specific social actor involved[24] (Munoz et al. 2014; Wang et al. 2025).

[23]Until 2015 was known as the European Photovoltaic Industry Association or the EPIA.

[24](A separate domain of criticism relates to grid parity's engagement with policy. Since the goal of this chapter is to isolate policy support from market developments over time, this aspect is not addressed here.)

I acknowledge these criticisms and argue in favour of applying the concept in a regulated electricity market context, such as in India's. Here, electricity prices are largely determined by long-term power purchase agreements (PPAs). According to Chattopadhyay et al. (2023), approximately 90% of the total wholesale electricity trade in India occurs through these bilateral contracts. In other words, variability or technical constraints do not translate into financial ones, thereby limiting price volatility, which is typically absorbed by the government or public enterprises. This relatively stable market environment makes it both easier and more meaningful to compare solar costs to fixed electricity price benchmarks, and also assign them to who bears the cost. Moreover, I consider grid parity a proxy for cost competitiveness[25], and interpret it in a context-sensitive way to understand the evolution of solar economics across Indian states based on past policies.

In doing so, I compare the cost of solar electricity generation to a range of electricity prices and costs over time. Next, I assess solar's competitiveness for two key entrepreneurial actors in the power sector: solar developers (who invest in and install solar projects) and off-takers like state DISCOMs (who procure electricity from various power producers, including solar, and resell electricity to diverse consumer segments). In this way, I reinterpret the idea of grid parity to suit the Indian context, defining parity when, where, and for whom. For the sake of coherence, these specifics on the methodology are included in the chapter itself. Ultimately, I analyse how achieving parity (or improving cost competitiveness) shapes these actors' behavioural responses in promoting solar growth. In other words, I examine how parities co-evolve with the ability of developers to install new solar capacity, and of DISCOMs to contract new capacity through solar auctions.

Besides LCOE, I use four additional price and cost parameters. First, the weighted average Auction Tariffs (AT) extracted from 183 solar auctions (excluding hybrids) between 2010-2023, sourced from the Bridge to India utility-scale solar database (BridgeToIndia 2025). AT

[25] As opposed to measuring when grid parity will be reached to anticipate changes in technology growth or policy support.

reflects the marginal cost of procuring new solar for DISCOMs and the selling price of new solar electricity for developers, determined through competitive bidding. Not all states have conducted auctions in all years. In these cases, pan-India auction tariffs[26] or national weighted averages are considered. Second, the weighted average Wholesale Electricity Price (WEP), retrieved from the Indian Energy Exchange, is the area-specific market-clearing price from the day-ahead market between 2010-2023 (IEX 2025). This reflects the trading price at which all producers sell and all DISCOMs buy electricity, regardless of source. Kumar et al. (2022) notes that WEP is approximately 12 percent higher than bilateral PPA tariffs, making it a reasonable proxy for wholesale electricity prices. Therefore, third, the PPA price is estimated as 12 percent below the WEP. Fourth, the weighted average Power Purchase Cost (PPC) is retrieved from ICED's electricity distribution – power purchase database and covers 2015–2023 (ICED 2025). PPC reflects the actual weighted-average cost DISCOMs pay to procure electricity from various sources (e.g., solar, coal, wind, large hydro, and nuclear) under all existing contracts[27]. All values are converted to 2023 USD using the RBI INR-USD exchange rate (RBI 2024) and the FRED GDP deflator (St.Louis and of 2024)to ensure comparability with IRENA's cost values[28].

3.2.3 Measuring policy effort (Chapter 6)

To measure policy effort, I draw on methods from political science and policy analysis. Lieberman and Ross (2024) argue that climate policy effort can be assessed based on three things: policy commitments (or targets), policy actions (or concrete policy measures adopted), and policy outcomes (or, in this case, technology growth). I measure policy effort based on the first two and map these alongside observed patterns of solar growth over time and space. I also include the other social actors in this analysis - national and subnational governments, political and technical decision-making bodies, and private-sector actors such as solar manufacturers. I

[26]As these could technically be installed anywhere (MNRE 2017).
[27]A graphical illustration of these costs is in chapter 5
[28]The conversion values are in the Appendix, Figure A.6.

see how policies influence and are shaped by vested interests and institutional capacity. The methods in this section adhere to the analysis in Chapter 6, which zooms in through the political lens.

Measuring change in policy commitments

Given that utility-scale solar growth in India is ultimately an aggregation of subnational growth patterns, it becomes essential to understand how target-setting and fulfilment evolve at both the national and state levels. Therefore, here I focus on, first, how and to what extent state-level commitments align with national goals, and how consistently states have set and met their targets. Second, whether targets are ratcheted up or down as technology grows.

In India, policymakers have set out two types of solar energy targets: (i) installed capacity targets, which specify the total MW to be deployed within the target year; and, (ii) Renewable Purchase Obligations (RPOs) targets, which require state DISCOMs and large consumers (e.g., open access users) to procure a certain share of their electricity from solar or other renewables. The first national solar capacity target was introduced in 2010 (GOI 2010). Since then, both national and state-level governments have periodically announced solar targets. At the national level, two major target years have been established - 2022 (initially set in 2010 and revised in 2015)(MNRE 2015b), and 2030 (CEA 2023; McGrath 2021). Beyond this, India has set a net-zero emissions goal for 2070 (McGrath 2021), but has not provided interim solar- or renewable-specific targets beyond 2030. At the subnational level, the 2022 target year remains the most widely adopted benchmark across states. However, several states have also set interim targets. The first national level solar RPO target was set in 2010 under the National Tariff Policy (Rao and Agarwal 2021) (p.18). Ever since, the RPO framework has been decentralised, with considerable variation across states in terms of scope and implementation mechanisms (Mannur et al. 2024). As a result, it would be methodologically inaccurate to directly compare RPO compliance rates across states (as discussed further in Section 3.2.1). As a result, I use national-level targets and compliance for RPOs [29].

Capacity target data over time and across states were compiled from policy documents, planning reports, media coverage, and official announcements. The 2022 state-wise targets are based on national allocations, while other years rely on individual state policies. Where targets are not explicitly divided between utility-scale and rooftop solar, I use a 60:40 ratio based on 2022 policy norms, where 60 percent of the capacity is to be met by utility-scale solar projects (MNRE 2015b). This ratio is applied to post-2022 targets unless otherwise stated. RPO target and compliance data are for 2018-2021 and are retrieved from the Indian Climate and Energy Dashboard (ICED 2025). All target values are in Table A.2 in the Appendix.

Measuring change in policy actions

To measure policy actions, I begin with the assumption that as solar technology grows, a corresponding policy mix or portfolio of policies evolves alongside it (Schaub et al. 2022). In theories of policy change, scholars have argued that there are two ways of looking at this mix: by policy objectives (or ”policy priorities”), and by the means or tools used to achieve those objectives (or ”policy instruments”). See Cashore and Howlett (2007); Hall (1993) for original classification and see Fernández-i Marín et al. (2025); Ollier et al. (2024) for its application in energy and climate action. Here, I measure policy effort based on the density of policy actions using methods from Schaub et al. (2022).

Data used for this analysis is derived from Bridge to India’s Utility-Scale Policy Database (Bridge To India 2024). The database includes both planned and implemented policies, covering both currently active and terminated policies. The technology focus in the database is not only on solar but also includes all RE technologies. I exclude policies that are specifically related to rooftop solar, off-grid applications, or hydrogen, to focus on those that have utility-

[29] For state-specific RPO target data refer to Table A.2

scale solar within their scope. I also exclude policies classified as 'drafts' (or those that were planned but never formally adopted or are yet to be adopted). After applying these filters, the final dataset includes 532 policies (147 national and 385 state) between 2004 and September 2024. Of this, 204 have been terminated (31 in national and 173 in state). The final dataset includes both legally binding regulations, like laws, and more voluntary programs, such as initiatives and schemes. It also includes administrative orders that clarify or extend existing policies.

To measure effort, I classify policy documents first by their priorities and second by the instruments used to address these priorities. Policy priorities are defined as barriers that policymakers aim to overcome at different stages of technological deployment. In other words, I conceptualise policy priorities as representative of barriers a technology encounters throughout its growth trajectory. This approach departs from existing literature that examines barriers from the perspective of actors or adopter groups of a given technology (Bergek and Mignon 2017; Kanda and Hjelm 2021; Neij et al. 2017; Río and Unruh 2007). Instead, I consider barriers from the broader perspective of policymakers' efforts towards a given technology. From this conceptualisation, my approach encompasses a wider range of actors and system-level considerations.

With no established classification system based on policy priorities, I developed one through a bottom-up, iterative process. The process began by manually classifying each policy according to the specific barriers it sought to address. These included barriers related to curtailment, balancing electricity demand and supply, grid interactions during captive consumption, grid capacity limitations, intermittent RE generation, limited wholesale electricity trade, the poor financial health of DISCOMs, etc. These individual barriers were subsequently grouped into broader categories such as grid integration, electricity trade and dispatch, institutional development, and grid expansion. At the top level, these categories were further cumulated into two overarching policy priorities. The first, system integration, refers to the non-physical integration of solar energy into existing systems. The second, complementary technologies and infrastructure, encompasses policies targeting the physical integration of solar electricity, such as those focused on expanding transmission infrastructure and developing storage capacities.

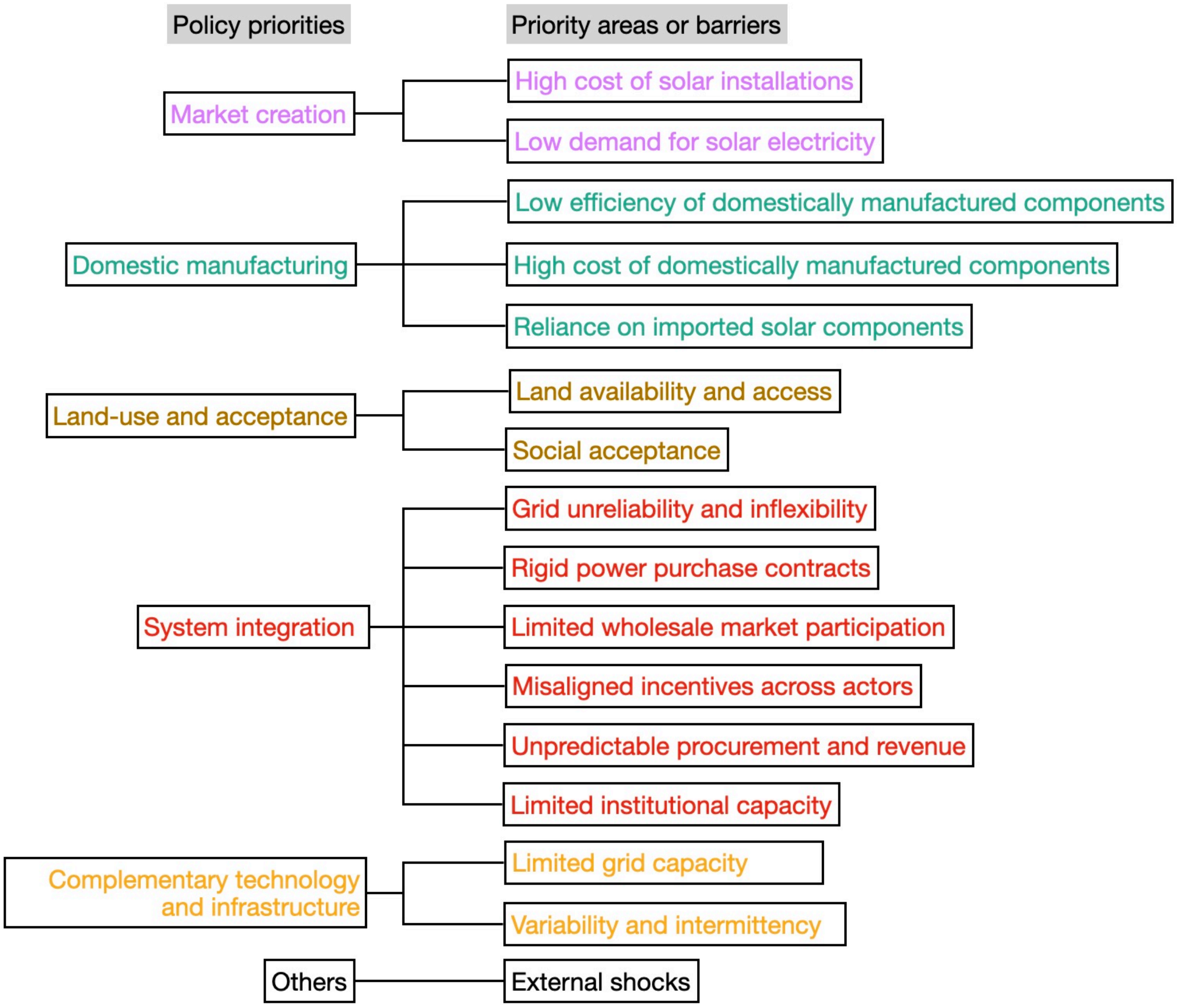

Figure 3.4: 2-level classification of policy priorities

The process of naming and identifying the top-level policy priorities involved assessing recurring themes in the literature. For instance, (Breetz et al. 2018; Markard 2018; Ollier et al. 2024) show that system and grid integration policies emerge at later stages of technological growth, whereas Breetz et al. (2018); Gallagher et al. (2012); Nemet et al. (2018) emphasise technology push and pull policies are characteristic of early-stage technological development. In this dissertation, the latter is cumulated under market creation priorities. The resulting classification thus combined insights from the literature with a manual review of context-specific policy realities. Initial policy categories were progressively grouped into broader ones and refined through iterative feedback, including discussions with my supervisors and insights from Nacke et al. (2024), who simultaneously classified policy actions for onshore wind in Germany. In cases of ambiguity, I consulted with the group to ensure consistency and conceptual clarity. Through this collaborative process, we arrived at a two-level classification comprising six top-level policy priorities, used to understand the diversity and evolution of policy actions. See Table 3.2 and Figure 3.4 for a detailed definition and classification of policy priorities.

Policy priorities	**Definition**
Domestic manufacturing	Policies relating to local solar component production.
Market creation	Policies relating to capacity deployment.
System integration	Policies relating to the non-physical integration of solar electricity within existing systems.
Complementary technology and infrastructure	Policies relating to the physical integration of solar electricity within existing systems.
Land use and acceptance	Policies related to land use and social acceptance for solar projects.
Others	Policies not included in above.

Policy instruments	**Definition**
Economic	Policies where policymakers need to spend money.
Regulatory	Policies where policymakers make rules or regulations that shape market or actor behaviour.
Target-setting	Policies where policymakers set targets to achieve broader climate or development goals.
Policy support	Policies where policymakers make strategic long-term plans and create necessary implementing bodies to implement these plans.

Table 3.2: Definition of top-level policy priorities and instruments

Next, I follow a similar approach when classifying policy instruments. Policy instruments are defined as tools of intervention used to address specific policy priorities. Given the extensive nature of policy classifications based on instruments, I draw on insights from existing schemes developed in prominent publicly available databases. This process began with a review of Schaub et al. (2022), who compared the classification structures of several major climate policy databases. I primarily draw from the NewClimate Institute's Climate Policy Database (NCI 2024), which compiles climate change mitigation and adaptation policies from official sources and multiple databases covering 196 countries across a wide range of sectors. This database proposes a 2- to 3-level policy classification scheme based on instruments, which I adopt to classify Indian solar policies. To accommodate "orphan" policies, i.e., those that do not fit neatly into existing subcategories, I integrate additional subcategories from the LSE-Grantham Research Institute's Climate Change Laws of the World (GRI 2024) (also discussed in Schaub et al. (2022)) and work by Callaghan et al. (2025) at the Mercator Research Institute. Here, too, through a bottom-up iterative manual coding approach, I arrive at a 2-level classification comprising of four top-level policy instrument categories. Tables 3.2 and 3.4 provide an overview of the two-level classification, while a detailed three-level representation is presented in Figure **??**.

I distinguish between national and state-level policies to capture differences in policy effort across governance levels. I calculate policy density and track the diversity of priorities and instruments in three steps. First, I identify the expiration year of policies that were classified as terminated based on the control period or validity information within the policy document. In cases where such information was absent, I assume the policy remains active for three years following its last amendment or update (including clarifications, extensions, or corrections). For policies adopted in or after 2022 with no specified end date but marked expired, I assume expiration in 2024. Policies terminated in year *t* are excluded from policy density calculations beginning in year *t+1* (following the approach in Schaub et al. (2022)).

Second, I calculate policy density as the sum of the total number of active policies in a given year. For this, each policy is counted as 1. When a policy addresses multiple priorities or employs multiple instruments, I divide the weight equally among them. For example, the 2018 national Wind-Solar Hybrid policy supports solar-wind hybridisation, includes local content requirements, and provides guidance for grid integration. It therefore receives 0.25 weight for each of the following priorities: market creation, system integration, domestic manufacturing, and complementary infrastructure.

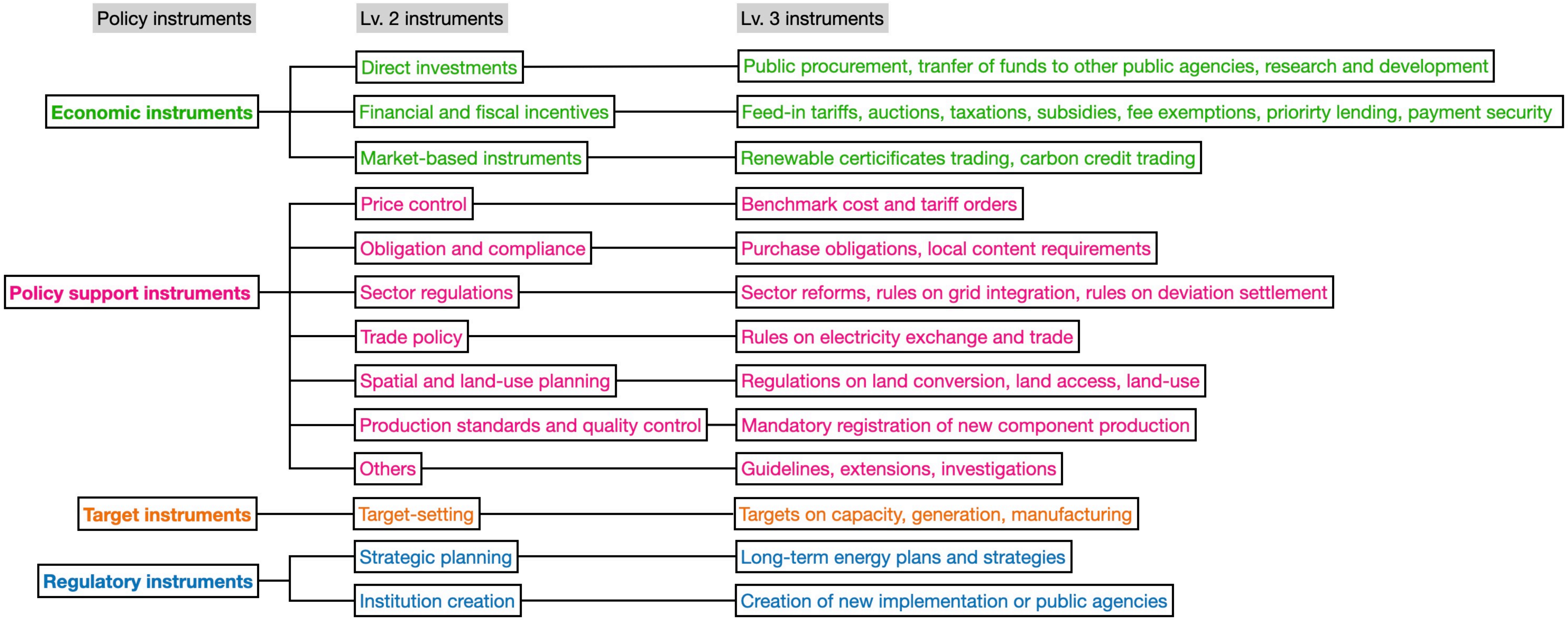

Figure 3.5: 2-and 3-level classification of policy instruments

Finally, I capture a snapshot of which policy instruments are used to pursue which priorities at both the national and state levels. For this, I assume that each instrument associated with a policy equally supports all priorities. While this may not always reflect reality, I observe that the overlaps this system creates are relatively minor and do not lead to misleading results. For instance, Figure 6.8 shows that in states, targets are used to implement land use-related priorities. Yet, states rarely set explicit land-use targets. These patterns emerge because state-level solar policies, which aim to address a mix of priorities, often include land acquisition guidelines alongside market and infrastructure support, which incorporate target setting.

Measuring vested interest and institutional capacity

To assess vested interests[30], I begin by mapping the governance and organisational structures of key actors and institutions involved in power policymaking, implementation, and electricity generation, transmission, and distribution (see Figure 6.1). This helps reveal ownership patterns, which form the foundation for understanding vested interests of the three main actor groups examined in this research: political actors (such as national and state policymakers), state-owned power utilities (such as DISCOMs and other implementation bodies), and private enterprises (such as solar developers and supply chain participants). Existing literature on ownership models — especially the differences between state-owned and private entities — provides valuable insights into their motivations, exposure to political influence, access to finance, and risk appetite (Steffen et al. 2022). To explore additional nuances and how vested interests and institutional capacity have changed over time, I analyse trends in the diversity and market share of solar developers involved in installed projects, as well as the diversity and participation of public sector off-takers[31] conducting solar auctions. The data for this analysis is drawn from Bridge to India's utility-scale solar database, which covers the period from October

[30]While part of the political perspective, a major part of the analysis on vested interests and institutional capacity is presented in Chapter 5, which focuses on the techno-economic perspectives. This highlights the co-evolving relationship between political and market systems, where developments in the solar market influence political outcomes, and political decisions, in turn, shape market dynamics.

[31]Off-takers are those who conduct solar auctions

2010 to September 2024. It includes 296 successful auctions, representing a total of 165 GW in allocated capacity and involving over 95 developers who have been commissioned a capacity of 120 GW.

To contextualise interests and capacities, here I briefly outline how solar energy is auctioned and installed in India, and how the various actors interact within this system. Most of India's solar capacity has been developed through competitive auctions. These auctions are shaped by rules set by policymakers. In 2017, the Ministry of New and Renewable Energy (MNRE) issued standard bidding guidelines to streamline and harmonise the auction process and improve transparency. Auctions are typically conducted by different types of off-takers — primarily state-owned utilities, such as state DISCOMs, as well as national-level entities like NTPC and the Solar Energy Corporation of India SECI). In recent years, large commercial and industrial (C&I) consumers[32] have also started floating tenders more actively. Solar developers bid in these auctions, and the winning developers sign a Power Purchase Agreement (PPA) with the off-taker that issued the tender. India's first solar auction was held in 2010.

A typical auction process begins when an off-taker issues a Request for Proposal (RfP), specifying the total MW capacity it intends to procure. Developers that meet the technical and financial criteria submit proposals, usually for capacities above 50 MW, along with an initial price/tariff offer in INR/kWh. The top 80% of qualifying developers (lowest bids) then enter an electronic reverse bidding phase, where prices are competitively reduced. The winners secure a 25-year PPA that specifies both the project size and the tariff at which electricity generation from that project will be sold. This tariff is fixed and generally not indexed to inflation (Egli et al. (2023), Table A.2). To prevent market concentration, regulations place limits on how much capacity a single developer can win, although these thresholds are sometimes influenced by pressure from larger firms. While PPA terms can vary slightly across different off-takers, developers are typically required to meet a minimum capacity utilisation factor (CUF) of 17%.

[32] They float tenders to build solar projects for captive consumption.

Failing to meet this generation target can lead to penalties ranging from 25–50% of the agreed tariff. Any generation beyond the contracted amount can be sold on the open market or bought by the off-taker at 75% of the PPA rate. Project timelines and delivery milestones are outlined in the tender documents, although in practice, they may shift due to implementation delays or renegotiations. Typically, the time from RfP issuance to project commissioning is around 3.5 years[33], and from auction result to commissioning is between 2-3 years[34] (based on Rustagi and Chadha (2020), table 6, for auctions by SECI).

3.2.4 Establishing causal links

While the previous sections examined the evolution and co-evolution of systems within each perspective using quantitative methods, a central challenge remains: identifying the causal links driving these dynamics. To uncover these links, I use process tracing, grounded in Hedström and Ylikoski (2010) and Little (2015) mechanistic view of social explanation. Hedström and Ylikoski (2010) define mechanisms as "constellations of entities and activities organised such that they regularly bring about a particular type of outcome." They view the social world as contingent, heterogeneous, and path-dependent, yet still shaped by socially recurring patterns that form discoverable pathways from cause to effect (Little 2015). My goal is to identify such recurring regularities that explain how and why outcomes (here, solar growth) occur in specific -and thus comparable (here, developing country) contexts.

Process tracing, as described by Beach and Pedersen (2019), is a qualitative method designed to build and test causal explanations within case studies. Unlike correlational analysis, it unpacks the sequences linking causes to effects, thereby revealing how and why outcomes emerge. Mahoney (2012) emphasises that this method shows "(1) that an initial event or process occurred, (2) that a later outcome followed, and (3) that the first caused the second". Both Bennett and Mahoney have argued for using the method in analysing complex multi-dimensional and histor-

[33] 42 months, or about 36 months when the auction is linked to a solar park

[34] 39 months or about 33 months when the auction is linked to a solar park

ically situated social outcomes (here, energy transition) with multiple potential causes, where linkages need to be disentangled. To do this, I follow a three-part approach to establish causal links.

First, I develop a theory-guided hypothesis, informed by existing literature (Beach and Pedersen 2019). It enables me to identify which event sequences are relevant to test. For instance, a recurring idea in energy transition research is that once renewables become cost-competitive, governments can withdraw policy support. This hypothesis forms the starting point of the causal story I investigate. **Second**, I collect empirical evidence to test whether the hypothesised process unfolds in reality. This involves examining data on solar cost trends, technological growth, and shifts in policy support. Central to this step is reconstructing the temporal order of historical events - identifying what occurred first, what changed subsequently, and how key actors responded. The aim here is to construct a causal narrative that is logically coherent, empirically grounded, and theoretically informed. Mahoney (2012) refers to this type of historical reconstruction as prospective process tracing. Geels (2022) calls it event chain causality in which change unfolds through a cascading sequence of interdependent, temporally ordered events. This process-oriented and historically specific perspective emphasises the role of feedback loops often prevalent in Geels' work. For example, I investigate how intensified market competition influences the capacity of firms to engage in solar development. Those that can survive this competition consolidate into an interest group capable of influencing policy change. These sequences of events then feed back into new policy adoption, market rules, and technology growth. In doing this analysis, my aim is not to discover entirely new mechanisms but to apply known ones[35] within specific socio-political contexts to evaluate their relevance and explanatory power. As Little (2015)(p. 472–474) notes, this is a problem-solving approach that draws on an existing repertoire of mechanisms to address tensions in the literature.

Third, I refine and test causal inferences by consulting additional evidence as needed, includ-

[35] Albeit, often includes those that were not evaluated in combination with one another previously.

ing academic literature, industry reports, and media sources. When encountering unexpected or anomalous outcomes, I also engage in retrospective process tracing — working backward to understand and explain the outcome — often by collecting additional data. For example, when an import tax initially slowed solar growth, but this effect was short-lived, I investigate why the impact was temporary (against popular sentiments at the time) and what countervailing forces came into play. A key component of this step is counterfactual reasoning — asking whether the observed outcome (here, imposition of an import tax, and a quick re-acceleration of growth) would still have occurred under different conditions (different cost levels, or a policy support package available) and isolating the one condition absolutely necessary.

It involves two steps: (i) examining whether the causal relationship holds across different times and places, and (ii) constructing historically plausible scenarios in which the hypothesised cause is absent. These counterfactuals avoid miracle conditions by introducing only minimal, realistic changes Mahoney (2012). For example, I ask whether the slowdown and the quick re-acceleration happen across all states. If so, then I look for cost and policy developments that were universal across the country. If not, I look for what areas led to re-acceleration and what cost and policy factors were at play there. This approach allows not only for testing existing theoretical claims but also for identifying contradictions or gaps in dominant narratives, offering potential to generate new theoretical insights. It also captures the political dynamics of energy transitions. For example, I examine how actors across regions respond to changing costs and policy conditions, in turn, shaping future technology, cost, and policy developments. Taken together, this structured, theory-informed, and evidence-driven approach allows me to disentangle complex, historically situated processes and explain how co-evolutionary outcomes — such as solar technology growth — unfold within a given context.

3.2.5 Anticipating future growth

The primary focus of this dissertation is to uncover the role of cost decline and policy effort in historically driving utility-scale solar growth in India. In discussing the implication of my results, in Chapter 7, I also look forward to anticipating potential future trajectories of growth. Grounded in both observed patterns and officially planned targets, I project how solar capacity might evolve by the end of the decade. This involves not only a temporal analysis — how solar capacity changes over time — but also a spatial one, looking at how these changes play out across states and regions. I conduct an exploration of three counterfactual scenarios that are based on a linear growth model. See Table 3.3. Each scenario is constructed at the state level and then aggregated to provide a national-level projection. To ensure comparability across states, I first normalise capacity additions to system size as of 2015. Then, I calculate the three-year moving average growth rate, which helps smooth out short-term fluctuations and irregularities in capacity additions. Plus, it preserves the core characteristics of growth in an emerging market, while allowing for more consistent comparison across geographies.

Scenario name	Basis of projection	Purpose	Outlook
MaxR3	Each state's highest observed growth rate	Shows potential if every state sustains or returns to best historical performance	Partially optimistic
LastR3	Each state's most recent growth rate	Estimates likely outcome if recent patterns persist	Partially pessimistic, Continuation of status quo
Target	Each state's targeted growth rate	Measures progress against stated ambitions	Planned growth

Table 3.3: Defining the three counterfactual growth scenarios

The **MaxR3**, or partially optimistic scenario, assumes each state sustains its highest observed growth rate. This represents an optimistic outlook as states with stagnant or stable growth are expected to accelerate, while those already expanding maintain their momentum. Although optimistic, it remains conservative by not assuming growth beyond either current acceleration (for fast-growing states) or past peak performance (for stable or stalling states). The **LastR3**, or business-as-usual scenario, projects growth strictly based on each state's most recent trajectory or last 3-years moving average growth rate. This represents a partially pessimistic view as accelerating states continue at their present pace, while stable or stalling states remain locked into their latest patterns. This scenario reflects the status quo and serves as the baseline for comparison. The **Target**, or planned growth scenario, relies on officially declared solar targets at the state level. It represents what policymakers deem feasible and captures the vision embedded in formal planning. Together, these three scenarios — two grounded in historical performance and one in policy ambition — offer a structured framework to anticipate national outcomes by the end of the decade. The comparison allows visualising not only India's likely solar trajectory but also reveals the degree of alignment between planned aspirations and empirical growth patterns.

3.3 Summary of research design

Figure 3.6 provides a graphical illustration of the research design in this dissertation, setting the stage for the empirical chapters that follow.

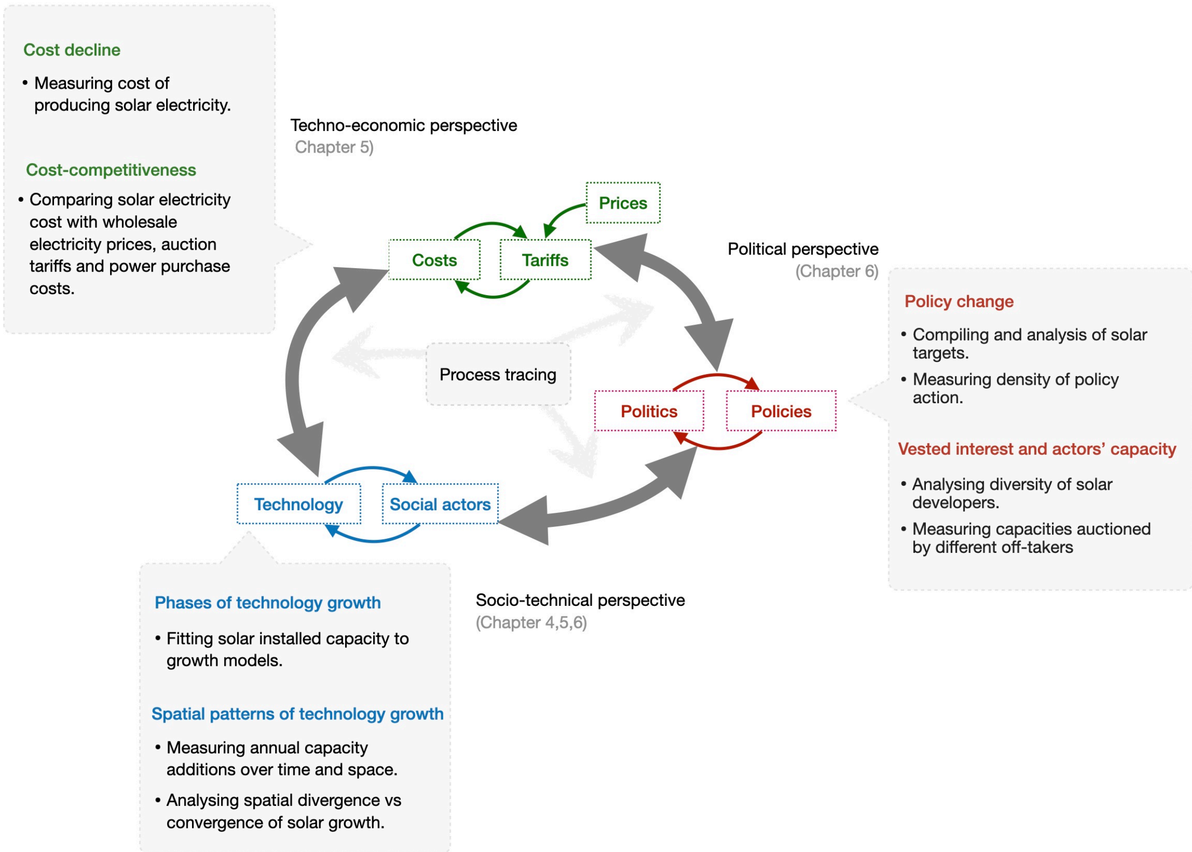

Figure 3.6: The research design of this dissertation

As an extension of the conceptual framework, this figure incorporates the methods used to look through each of the three perspectives (shown against the grey background). It also provides a brief overview of the analytical chapters.

4. Technology Growth and Diffusion

This chapter presents the temporal and spatial patterns of utility-scale solar growth in India. Here, I adopt the socio-technical perspective and focus on three main aspects: historical patterns of solar growth and diffusion in Section 4.1, factors influencing these patterns of growth based on existing literature in Section 4.2, and the remaining potential for future solar growth in Section 4.3. A final section summarises the main messages from this chapter.

4.1 Historical patterns of technology growth in India

Here, I first present findings on the temporal and spatial patterns of solar growth. In the second subsection, I address the convergence/ divergence debate from a subnational context. That is, whether late-adopting states in India grow faster or catch up with early adopters because the advantages of technology learning dominate, or contextual disadvantages persist, leading to continued divergence in growth.

4.1.1 Solar growth and diffusion in India

By the end of 2009, India's solar installed capacity stood at 10 MW, accounting for 0.0% of the total electricity supply. After 15 years, by the end of 2024, solar capacity stands at 75 GW (or 75000 MW), accounting for close to 8% of the country's total electricity supply. Nationally, solar reached the take-off point in 2014, contributing 0.5% of electricity supply and marking the end of the formative phase. Until this point, growth was slow and erratic, characterised by high costs. Since 2015, technology growth has been accelerating, marked by a period of exponential growth. A steady acceleration, with high year-on-year growth, continued until 2018. However, growth slowed momentarily in 2019-2020. From 2021, acceleration continued, yet the year-on-year growth rate was lower than that observed pre-slowdown.

Throughout, the adoption of solar in India followed distinct temporal patterns at the sub-national level. Early adoption was seen in the north-west, expanding first southward and eventually to the north-east. See Figure 4.1. Historical growth reflected the story of these three separate regions in the country. Until 2014, solar deployment was primarily led by the early adopters in the north-west, mainly Gujarat and Rajasthan. Between 2014-2019, the main contributors to solar adoption were three states from the south, mainly Karnataka, Andhra Pradesh, and Telangana. After 2020, the largest capacity addition shifted back to the earliest adopters in the north-west — Gujarat and Rajasthan. In contrast, growth in the southern region slowed, particularly in the states that had driven the pre-slowdown acceleration. Throughout, the north-eastern states did not make any significant contribution to the country's overall solar growth.

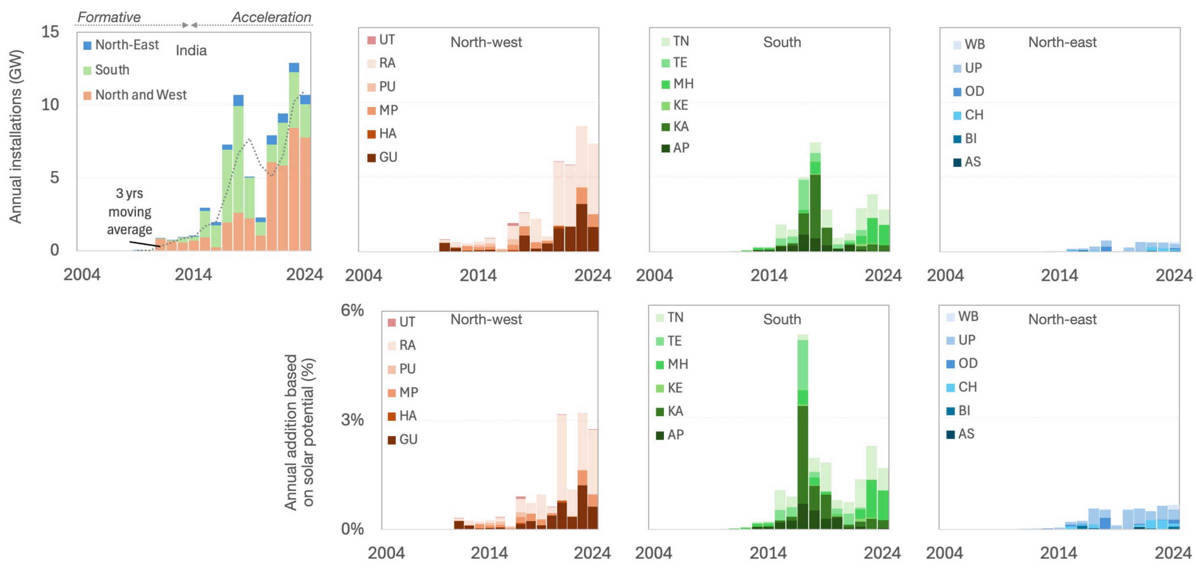

Figure 4.1: Solar installations over time and space in India
The top row shows annual installations at the national level, broken down by regions and further distinguished by states within each region. The bottom row shows annual state-level capacity additions relative to regional solar potential.

National-level solar growth is the cumulative result of technology adoption at the sub-national level. Hence, diffusion at the national level progressed more slowly than in individual states. While national growth continues to accelerate, growth phases vary across states. For example, solar is accelerating in five out of 18 states, including Gujarat and Rajasthan in the north-west, Maharashtra in the south, and West Bengal and Chhattisgarh in the north-east. The latter four of these states picked up pace only recently, whereas the first two have maintained a steadier and continuous trend. In the remaining 13 states, growth has either stabilised or begun to stall. See Figure 4.2. Thus, as of 2024, growth remains spatially heterogeneous within India. Absolute installed capacity ranges between 126 MW in Assam (in the north-east) to 22 GW (22290 MW) in Rajasthan (in the north-west). The leading state of Rajasthan alone has nearly twice the capacity of the second-highest state of Gujarat, which stands at 11 GW (11095 MW). Heterogeneity persists when deployment is adjusted for system size, ranging between 371.5 MW/TWh in Rajasthan to just 1.3 MW/TWh in West Bengal as of 2024.

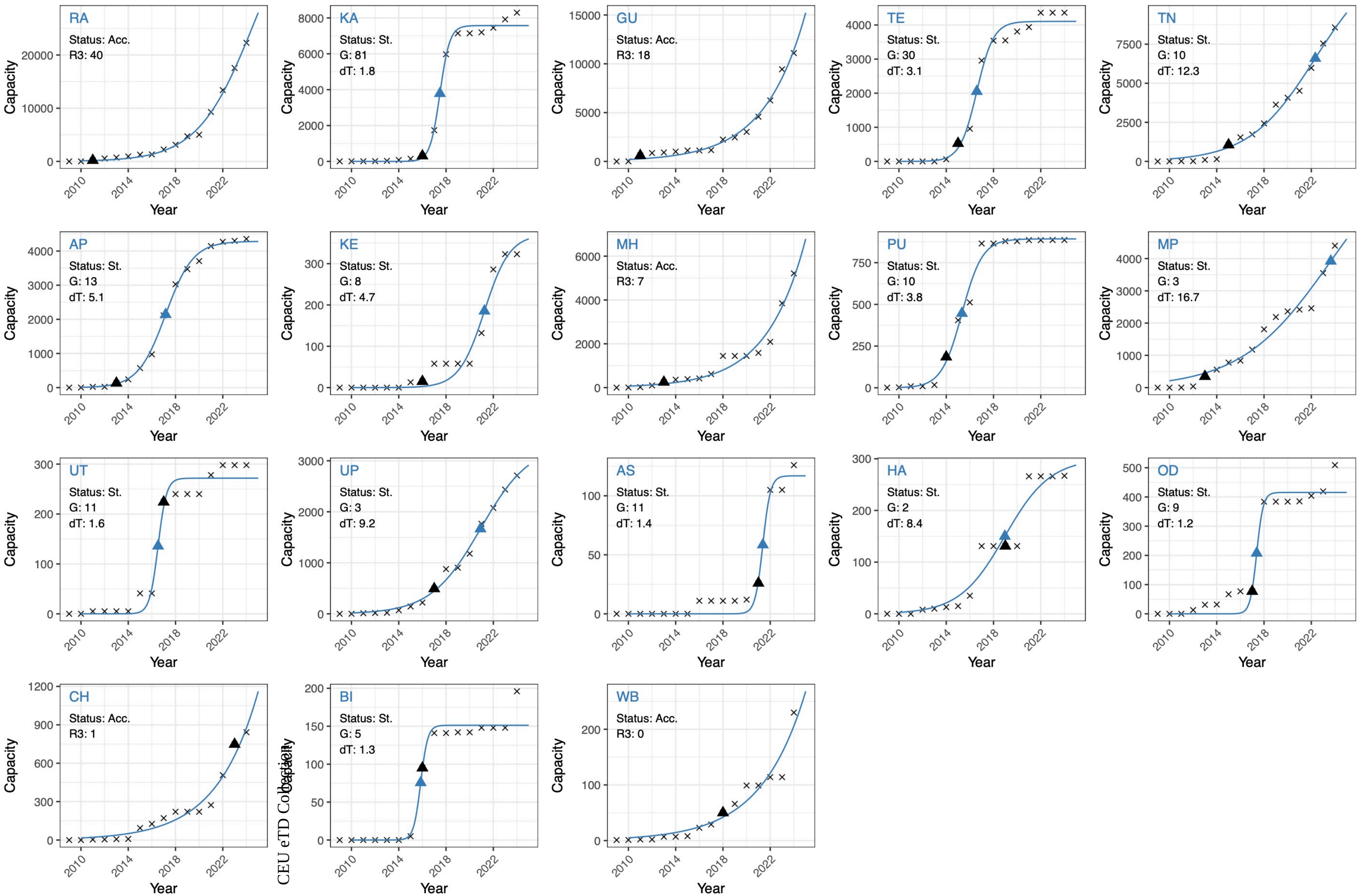

Figure 4.2: Solar growth phases across Indian states.

Status indicates state-level growth phases as of December 2024. "Acc." for acceleration and "St." for stable or stalling growth. The black triangle marks the point when solar reaches 0.5% of the total electricity supply (take-off point), while the blue triangle marks the point of maximum growth (inflection point). Growth rates are expressed as R3 for accelerating states and G for others, measured in MW per TWh.

4.1.2 Growth rates in early vs late adopting states

The top ten states leading in solar deployment are all early adopters, having achieved take-off before 2017. However, not all early adopters have emerged as leaders. For instance, Bihar achieved take-off in 2016 — the same year as the southern states of Karnataka and Kerala — yet it ranks very low in terms of installations. All leading states are concentrated in the north-west and the south, demonstrating that solar growth in India has been decisively driven by southern states, along with two north-western states, all of which were among the earliest adopters.

The diffusion literature holds three main positions on how technologies diffuse over time and space (Section 2.4.2). One, where the advantage of technology learning and experience dominates. This view suggests that while late-adopting regions take longer to adopt a new technology, they experience faster growth once adoption begins. The advantage comes from the technological learning and policy experience accumulated by early adopters. However, despite higher growth rates, the overall adoption level (measured here as total installed capacity) in late-adopting regions may remain lower than in early adopters (Grubler 1996; Wilson et al. 2013). This is the convergence argument. The second position is where contextual disadvantages dominate. According to this view, delayed adoption reflects unfavourable conditions or structural constraints in certain regions. These factors not only postpone initial adoption but also limit the pace of subsequent growth. Consequently, late adopters fail to replicate the rapid expansion achieved by early adopters (Comin and Hobijn 2004). This is the divergence argument. The final position comes from those offering the balancing view. They argue that both dynamics operate simultaneously (Cherp et al. 2021). Late adopters benefit from technological learning and knowledge spillovers, but these gains are offset by structural and contextual constraints. As a result, growth rates converge, with late adopters and early adopters experiencing similar trajectories over time. In other words, this position finds no evidence for convergence.

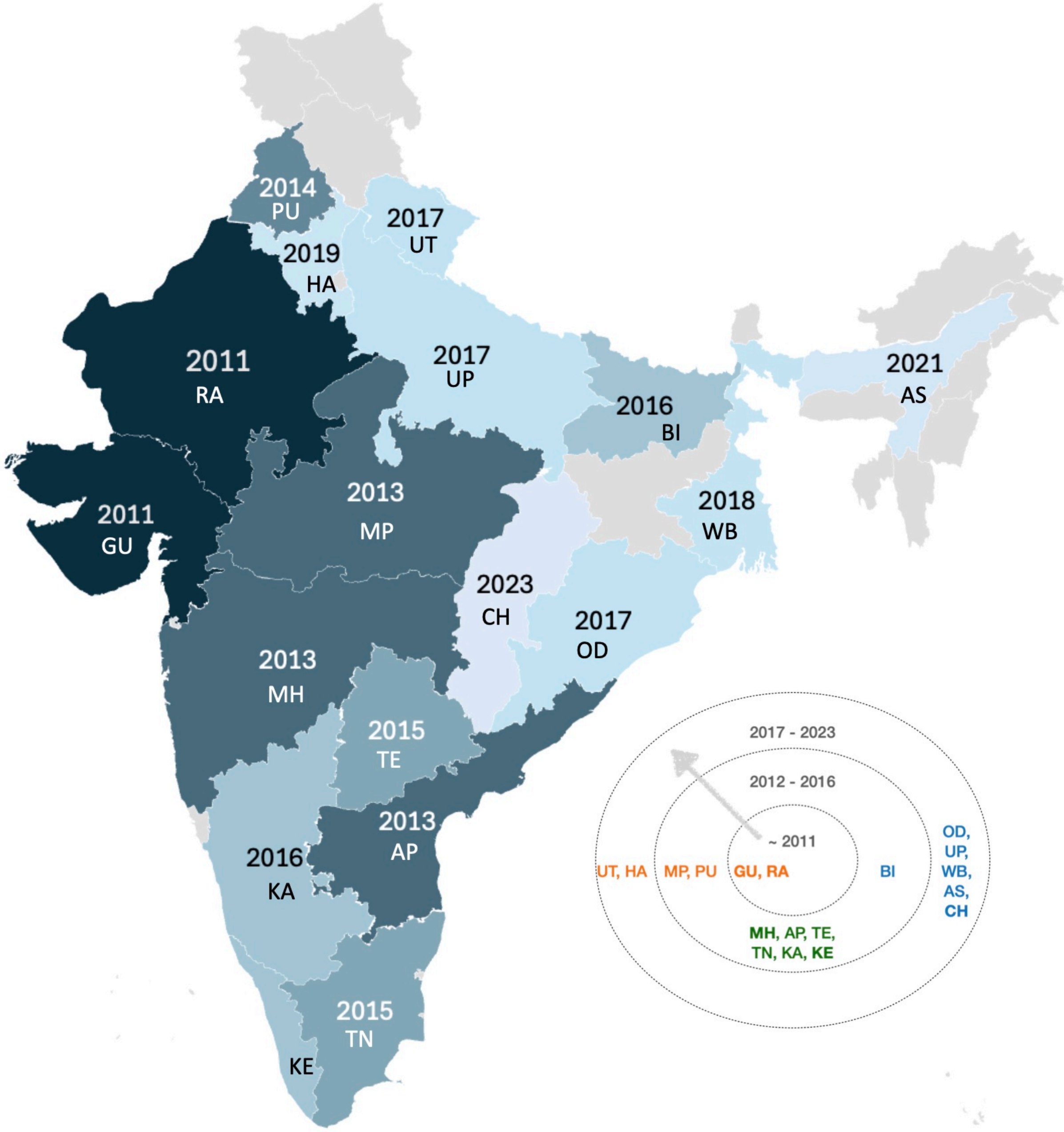

Figure 4.3: Timing of solar adoption across Indian states

Timing of take-off. Darker areas on the map indicate earlier adoption. The concentric circles at the bottom right illustrate solar diffusion from the core to the rim and periphery.

In the case of utility-scale solar in India, the relationship between the timing of adoption and the highest growth rates achieved is positive but not statistically significant. This indicates that while early adopters have generally experienced higher growth rates, the overall pace of growth across states has remained relatively consistent over time. In Figure 4.4, I plot the take-off years for utility-scale solar across states (x-axis) against the maximum growth rates observed (y-axis), distinguishing between states where solar growth is still accelerating (peaks) and those where growth has stabilised or stalled (dots). Rajasthan and Gujarat, the two earliest adopters, achieved the highest levels of solar deployment in both absolute and relative terms, and solar growth continues to accelerate in both. When Rajasthan is excluded from the sample, the relationship between take-off and growth rates becomes even weaker. Apart from these two states, Karnataka and Telangana in the south, though not among the earliest adopters, experienced comparatively faster growth, but only for a short period around 2017 (see Figure 4.1), after which growth has stalled. The absence of a significant relationship between timing of adoption and maximum growth rates lends support to the balancing effect theory, suggesting that maximum growth rates are broadly consistent across states regardless of when adoption began.

Yet, anticipating the exact evolution of growth phases beyond the formative stage, and therefore estimating maximum growth rates at the state level, remains uncertain. At present, solar adoption is accelerating in five of the 18 states, suggesting that growth rates in these states are likely to rise further. So, growth rates can change for both early and late adopters. Plus, states where growth has stabilised or is stalling may still experience renewed acceleration in the future. Maharashtra and West Bengal illustrate this pattern. Despite achieving take-off in 2013 and 2018, respectively, they saw little growth for a very long time before starting to pick up pace in recent years. Overall, solar adoption patterns in India can be grouped into three categories. First, states that continue to experience sustained, continuous growth, such as Rajasthan and Gujarat. Second, states where growth evolves in pulses, stalling temporarily but then rebounding after shorter or longer intervals — such as Haryana, Madhya Pradesh, Maharashtra, and Tamil Nadu.

Third, and most common, are states that undergo a rapid growth phase for a brief period before plateauing, including Punjab, Andhra Pradesh, Karnataka, Odisha, Telangana, Uttarakhand, Assam, and Bihar. See Figure 4.2. But why does solar grow differently across Indian states?

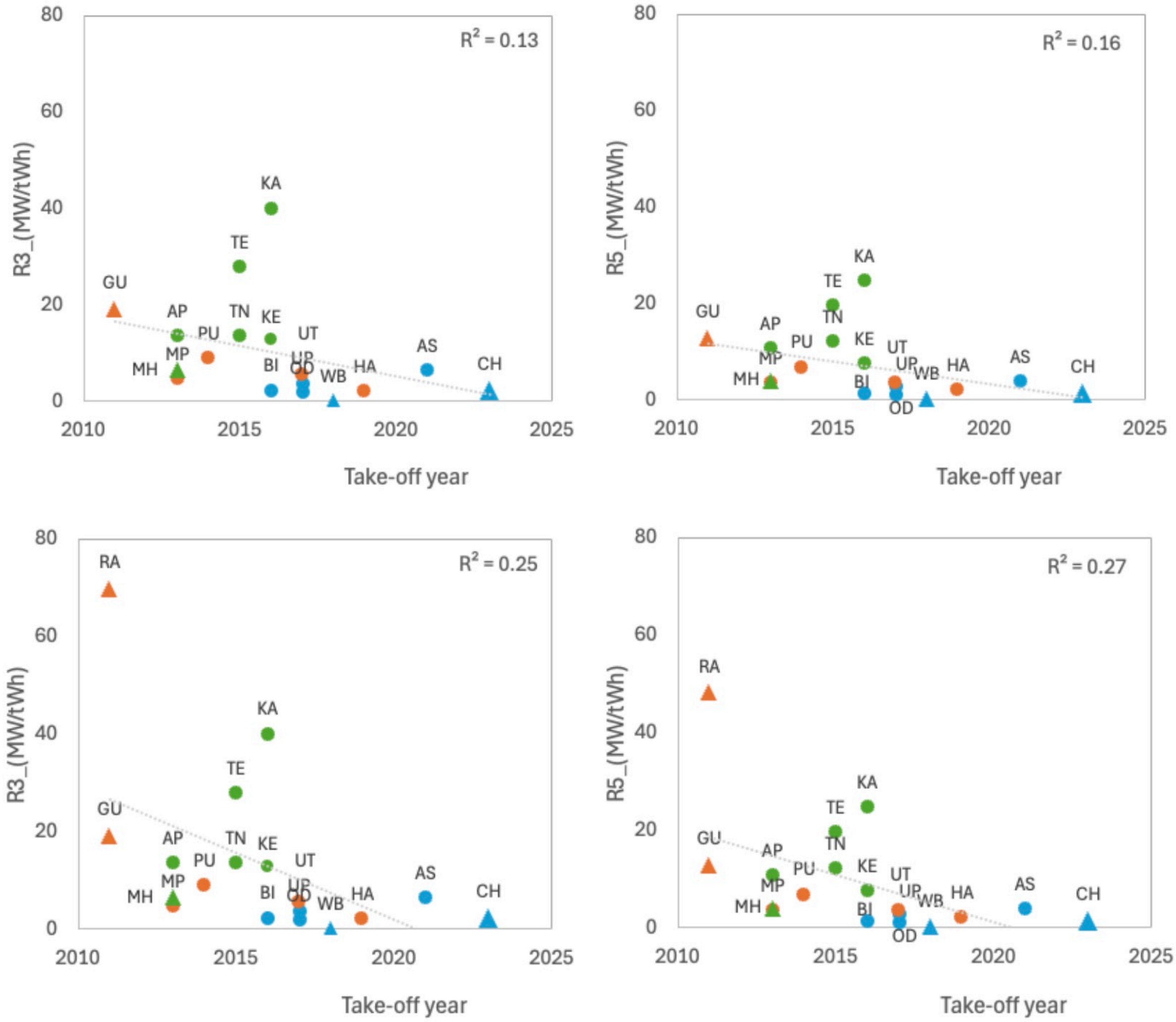

Figure 4.4: Take-off versus maximum growth rates among Indian states
The figure shows that later-adopting states do not exhibit higher growth rates. The right column presents growth as a maximum three-year moving average, while the left column uses a maximum five-year moving average. The top row excludes Rajasthan, and the bottom row includes it.

4.2 Factors driving solar growth across states

The first solar power plant in India was installed in Asansol, West Bengal, in the north-east — a 2 MW project commissioned by the West Bengal Renewable Energy Development Agency and supported by the then state leadership (Jolly 2017; Sharma et al. 2012). Despite this early milestone, solar achieved take-off first in the north-west, in Gujarat and Rajasthan, in 2011. Since then, the trajectory of solar growth has varied sharply between these regions and more broadly across Indian states. 11 studies have examined the reasons behind these spatial differences in growth. See Table 4.1. While these studies adopt different methodological approaches, they converge on three key factors shaping spatial heterogeneity.

First, the **geophysical context** plays a decisive role. Higher adoption is associated with states receiving greater solar irradiance and offering more land availability. The leading states in solar development are primarily in the south and the north-west. They benefit from the country's highest levels of solar irradiance and relatively large availability of land. Importantly, they are also less locked into legacy energy infrastructures such as coal-based or large hydroelectric generation. See Figure 4.5. By contrast, most northeastern states lie within India's coal belt, while states such as Uttarakhand and Punjab (north-west), Assam (north-east), and Kerala (south) are smaller and historically reliant on hydropower. See Figure 4.6. With established generation bases and greater competing land-use pressures, these states have shown less urgency in adopting solar alternatives.

The rise of solar-rich states offers new opportunities for surplus generation and interstate electricity trade. Historically, however, coal-rich states supplied surpluses, while smaller states, in particular, faced deficits and relied on imports, shaping existing transmission infrastructure within the country. In other words, surplus generation in the north-west may not immediately be available to the rest of the country without the necessary development in transmission. See Figure A.7 in the Appendix.

Publications	Approach	Solar technology	States covered	Factors analysed	Factors affecting growth
Pandey et al 2012	Literature review	Solar	Rajasthan		Early mover advantage, solar potential, state policies
Schmid 2012	Econometric	RE	9 states		Key national and state policies, investment from the private sector
Hairat and Ghosh 2017	Econometric analysis	Solar	17 states	States GDP, population growth, electricity prices, Solar potential	Solar potential
Jolly 2017	Institutional entrepreneurship	Solar PV	Gujarat and West Bengal		Motivation of different state-level public and private actors. Solar potential, DISCOMs financial health and pre-existing industrial infrastructure.
Sareen 2018	Interviews	Solar	Rajasthan and Gujarat		Contextual conditions like, potential, institutions, politics
Sareen and Kale 2018	Political economy and energy justice	Solar	Rajasthan and Gujarat		Regional peculiarities and path dependence
Thapar et al 2018	Econometric analysis of determinants influencing 32 solar auctions	Utility-scale solar PV	15 states	Solar power potential, Capacity targets (national govt.), RPO targets (state govt), per capita income, cost of funds (or banks' lending rates), Energy demand, share of renewables, module prices, ATC loses/ off-taker's profile, contracted capacity through auctions, share of solar capacity subscribed for a tender.	For state-led auctions: Capacity targets (national govt.), RPO targets (state govt) DISCOMs or off-takes profile. For national-led auctions: Solar potential, cost of funds, module prices, and availability of solar parks.
*Bhowmik 2020**	Mixed methods: profitability and literature review	Utility-scale solar	6 states		Profitability determined by CAPEX, solar tariffs, solar potential, richness of states, availability of conventional energy sources, and sector performance
Shrimali et al 2020	Econometric analysis across different policy interventions.	Utility-scale solar and solar rooftop.	20 states	Policies: accelerated depreciation rate, MNRE VGF amount (Capital subsidy), RPOs, solar park capacity. Controlled for: average retail tariff residential, GDP DISCOM rating, ease of doing business, AT&C losses, electricity consumption per capita, total electricity generation, share of RE generation.	Solar parks and RPO targets. Plus, richer states and states with better DISCOMs have more solar deployment.
Busby and Shidore 2021	Political economy	Utility-scale solar PV	19 states	Solar irradiance, power deficits, DISCOMs financial health, coal costs, land access, political alignment of the state with the national government	Solar irradiance, DISCOM financial health, coal costs, and land access.
*Jhakhmola 2021**	Technology diffusion	Utility-scale solar PV	17 states	GDP, system size, growth in power demand, power supply deficit, solar irradiance, solar potential, coal transportation cost, DISCOMs health, ease of doing business, solar tariffs	Solar potential, favourable business environment, competitiveness with coal

Table 4.1: Existing knowledge base on the drivers of solar growth across Indian states.
Sources include Bhowmik (2020); Busby and Shidore (2021); Hairat and Ghosh (2017); Jakhmola (2021); Jolly (2017); Pandey et al. (2012); Sareen (2018); Sareen and Kale (2018); Schmid (2012); Shrimali et al. (2020); Thapar et al. (2018). Note that results for solar rooftop from Shrimali et al. are excluded. Additionally, Bhowmik (2020) and Jakhmola (2021) are Masters theses.

Second, studies highlight that the **financial health of state distribution companies** (or DISCOMs) plays a decisive role. While geophysical conditions determine the physical potential for solar deployment, DISCOMs play a pivotal role in ensuring that solar generation remains financially sustainable for developers. Acting as intermediaries between producers and consumers, DISCOMs facilitate power procurement and create stable market conditions for solar investments. Although Jakhmola (2021) finds no significant relationship between the timing of solar adoption and the financial health of DISCOMs, other studies Busby and Shidore (2021); Jolly (2017) suggest that states with higher solar deployment tend to have stronger, better-performing DISCOMs. These stronger DISCOMs are also concentrated in wealthier states, where greater economic resources allow more effective utility management and smaller power deficits (Shrimali et al. 2020).

The importance of well-functioning DISCOMs is most evident in their ability to honour power purchase agreements (PPAs), which are long-term contracts that provide revenue certainty for solar producers. In states where utilities face financial distress, solar deployment has been undermined by delayed payments, weak financial guarantees, and regulatory uncertainty (discussed further in Section 5.3.2). As a result, states with favourable geophysical potential but financially weak DISCOMs face challenges in scaling up solar. Whereas, states that lack both strong geophysical conditions and financially viable utilities are particularly unattractive, making adoption in these regions significantly low.

The third factor that studies highlight is **policy and political differences**. Some find that stability in government has been instrumental, while political alignment between state and central governments has not directly affected deployment. For instance, Jolly (2017) attributes Gujarat's early success — relative to West Bengal's weaker performance — to greater political stability within the state. Similarly, Sareen and Kale (2018) attribute political stability and institutional entrepreneurship in shaping the timing of adoption in Rajasthan and Gujarat. Gujarat initially led adoption, supported by better-performing DISCOMs that could offer higher

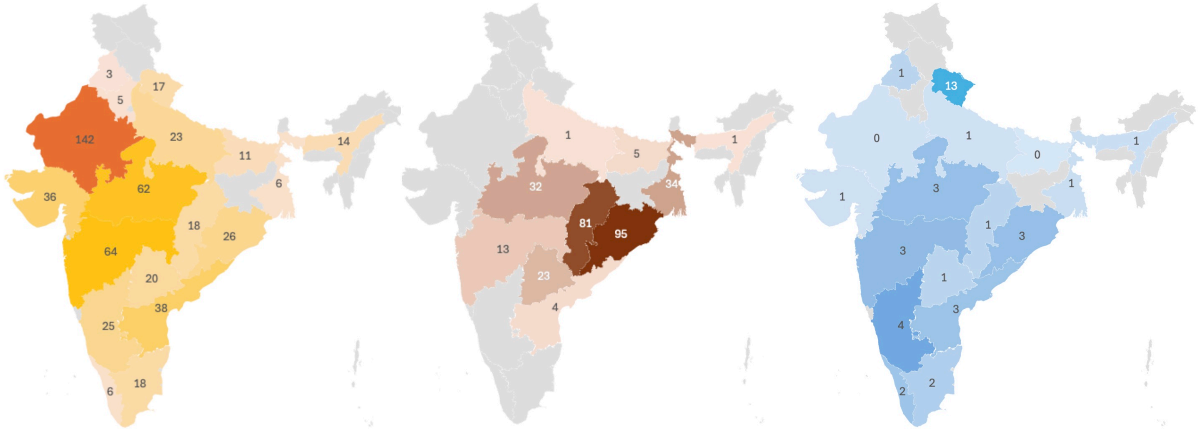

Figure 4.5: Energy resource potential across the 18 studied states.
From left to right: solar potential (GWp), coal reserves (billion tonnes), and large hydro potential (GWp). Own illustration based on Government of India data.

tariffs to solar producers (Shidore and Busby 2019). However, Rajasthan ultimately surpassed Gujarat in both absolute and relative installations, despite initially lacking the same degree of institutional stability. Therefore, while political continuity accelerated early adoption, long-term expansion depended on other aspects.

Shrimali et al. (2020) and Thapar et al. (2018) considered specific policies that were instrumental in driving solar growth. Two in particular stood out: solar parks and target setting (either through Renewable Purchase Obligations (RPOs) or capacity targets). Solar parks consolidate large-scale installations on pre-identified tracts of land, easing access and addressing one of the most significant barriers to solar projects — land access. See also (Busby and Shidore 2021). Capacity targets and RPOs, jointly set by national and state governments, act as demand pull policies — reflecting rising demand for solar power production.

Taken together, previous research shows that while geophysical potential provides the foundation for solar growth, it is state capacity and supportive policies that ultimately determine whether that potential is realised. Target-setting and establishment of solar parks, in particular, have proven especially powerful in guiding adoption. Yet, this evidence also points to an unfinished story of solar in India. Why have some leading states begun to stall? What has happened since the 2022 cut-off for most of the studies? To what extent have policies offset the barriers posed by DISCOMs' financial health? How have solar targets evolved ever since? And if targets and solar parks are the most transformative, do other policies matter? And how could one weigh the relative role of technology cost decline versus policies in accelerating solar? I take up these questions in the chapters that follow.

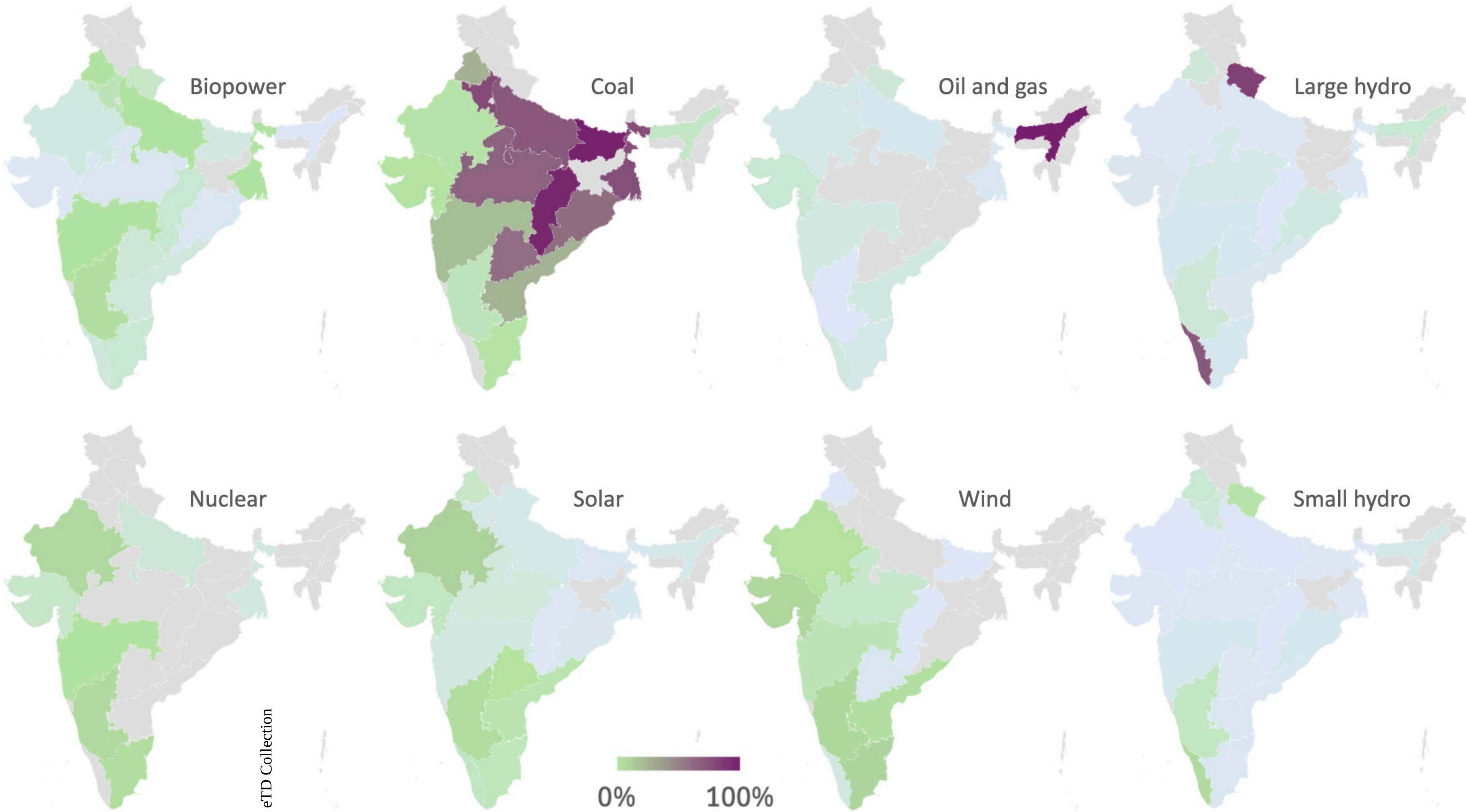

Figure 4.6: Share of different energy sources in total electricity generation across Indian states.
As of December 2024. Source: (ICED 2025).

4.3 Future potential for solar growth across states

The role of DISCOMs' capacity and specific policies warrants deeper investigation. These aspects are explored in subsequent chapters. Geophysical constraints, however, impose physical limits on how far either technological advancements or policy effort can drive solar growth in the country. Here, I evaluate the realised solar potential in Indian states. The National Institute of Solar Energy estimates potential based on solar irradiance, land availability, and climatic conditions, providing a scientific basis for decision-making within the Ministry of New and Renewable Energy (MNRE 2025a) (p.21). Since technology cannot overcome these inherent physical limits, the gap between a state's actual installed capacity and its theoretical potential represents the remaining space for future growth.

India's total solar potential is estimated at 750 GWp, based on the assumption that 3% of the country's wasteland area is covered by solar PV modules (MNRE 2025a). The 18 states studied here account for 534 GWp (or 70%) of the total potential. By the end of 2024, India had achieved 13% of this potential. Of this, 10% come from utility-scale and 9% from utility-scale installations in the 18 states studied. Potential varies widely across states, from as low as 3 GWp in Punjab (in the north-west) to as high as 142 GWp in Rajasthan (in the north-west). Regionally, the northwestern states exhibit the highest potential, led by Rajasthan, Gujarat, and Madhya Pradesh, followed by the southern states and then the north-east. The extent to which states have realised their potential also varies considerably. Figure 4.7 shows the potential achievement in each state and region, assuming that the remaining growth is met entirely by utility-scale solar installations.

Yet, regional patterns are visible. Both the north-west and the south have achieved similar shares of their potential, with the south slightly ahead. However, the distribution within these regions differs. In the north-west, solar capacity is concentrated mainly in Rajasthan and Gujarat, with a smaller share in Madhya Pradesh. Yet, progress towards achieving potential is

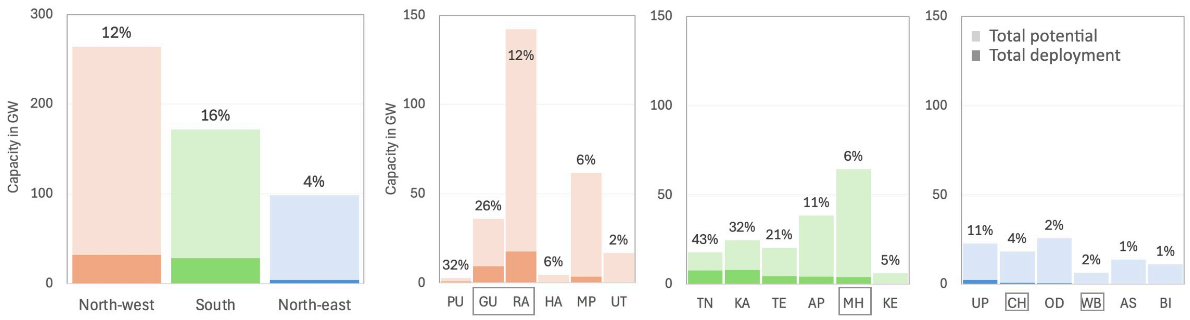

Figure 4.7: Solar potential and its achievement across Indian states and regions.
The figure shows outstanding solar potential. Lighter areas indicate remaining potential, while darker areas represent fulfilled potential. Percentages above the bars show the level of achievement. Boxed states across regions are those accelerating as of December 2024.

higher in Punjab, Gujarat, and Rajasthan. In the south, installations are more evenly spread across the states, reflecting a more diversified pattern. Yet, progress towards achieving potential is concentrated in Tamil Nadu, Karnataka, Telangana, and Andhra Pradesh. In contrast, northeastern states face both limited potential and slow progress in harnessing it. Yet, the most notable progress towards achieving potential here remains in Uttar Pradesh.

As seen in Figure 4.2, solar growth is currently accelerating in five states across the three regions, pointing to a pattern of focused acceleration during specific periods rather than uniform expansion across entire regions. Except for Maharashtra, the states driving acceleration in the north-east have lower potential than their regional counterparts and have achieved take-off only recently (Figure 4.3). Yet, the common feature in all three is that they have made relatively less progress in realising their solar potential. In contrast, the northwestern states of Gujarat and Rajasthan possess high potential, have made the largest strides in harnessing it, and yet continue to accelerate.

That said, significant untapped potential remains across all three regions. Most early adopters, who experienced higher growth rates, have also realised a greater share of their potential. Yet, expansion in many of these states is now stalling. While re-acceleration remains possible given the remaining potential, its likelihood and duration are uncertain. Plus, as noted in Section

2.2, late adopters, despite having more untapped potential, are not growing faster. Unlocking their capacity will take time, and historically, there are only two instances where late adopters outpaced early adopters: Karnataka and Telangana around 2017. See Figures 4.1 and 4.2. Yet, in both cases, this acceleration was short-lived, and growth has since stalled. Importantly, both states also benefited from relatively favourable geophysical conditions and the stronger financial health of their distribution companies. Policy efforts in lagging states, many of which lack these contextual advantages to succeed, must be more extensive and precisely targeted. Alternatively, if leading states continue to drive overall growth, it would be important to understand the relative role that cost decline and policies play in them.

4.4 Chapter summary

This Chapter took stock of the historical patterns of solar growth and diffusion in India, examined the factors influencing these patterns based on existing literature, and assessed the remaining potential for future solar expansion. Three main takeaways emerged.

First, India's utility-scale solar growth is a cumulative outcome of subnational trajectories shaped by geophysical conditions and the financial health of state distribution companies. While growth varies across individual states, clear regional patterns emerged in terms of both potential and realised capacity. The northwestern region holds the highest solar potential, led by Rajasthan, Gujarat, and Madhya Pradesh. Yet, significant deployment remains primarily in Rajasthan and Gujarat. The southern region follows in potential but, unlike in the north-west, has progress distributed more evenly across states. By contrast, the north-east combines low potential with minimal progress in harnessing it. Evolving growth patterns reveal that solar expansion is not uniform within regions but concentrated in high-potential areas at specific points in time. It is unclear at this point what causes these variations.

Second, the national growth trajectory went through four distinct periods, each with a regional focus. The formative phase (2009-2013) was led by early adopters in the north-west, primarily Gujarat, with Rajasthan and Madhya Pradesh also contributing. The acceleration phase began in 2014, marked a geographic shift southward. Karnataka, Andhra Pradesh, and Telangana drove rapid capacity additions until 2018, while growth in the north-west remained modest and dispersed. In 2019-2020 growth slowed down overall. Yet, from 2021, national acceleration continued with growth concentrated in the north-west — almost exclusively in Gujarat and Rajasthan. In the south, growth slowed, especially in the very states that had driven earlier expansion.

Third, substantial untapped potential remains across all three regions. Early adopters have realised a greater share of their potential, and several are now stalling. A few late adopters have recently started to accelerate. Yet late adopters, despite having larger reserves of untapped potential, are not growing faster. Only two instances exist where late adopters outpaced early adopters: Karnataka and Telangana around 2017, following policy interventions that eased land acquisition via solar parks. In both cases, however, acceleration was brief, and growth has plateaued since 2019. Moreover, both states benefited from relatively favourable geophysical conditions and stronger DISCOMs. No other late-adopting state has demonstrated compensatory acceleration sufficient to offset the slowdown of early adopters. This suggests that either leading states will continue to dominate overall growth, or lagging states will require dramatic interventions to meaningfully step up. In either scenario, differentiated policy approaches might be necessary.

This chapter provided an overview of the growth and diffusion of solar PV in India. Yet, it left several questions open. For example: what explains the regional shifts in growth? Why have some leading states begun to stall? If late adopters are expanding more slowly than early movers, to what extent do policies shape their trajectories? What role do the declining costs play? Do they compensate for the weak financial health of DISCOMs? These are the questions I take up in the following chapters.

5. Cost-competitiveness and Technology Co-evolution

The previous chapter established that solar growth varies across Indian states but follows clear regional patterns. At the national level, growth is accelerating and has unfolded in three distinct phases. Capacity additions were dominated by the north-west until 2013, by the south between 2014-2018, and once again by the north-west 2021 onwards. Based on past literature, spatial differences in growth are shaped by geophysical characteristics, the financial health of state distribution companies (DISCOMs), and policies like solar parks, capacity targets, and purchase obligations. Geophysically, the states in the north-west and the south lead in both solar potential and progress towards realising it, while states in the north-east lag on both counts. Nevertheless, significant untapped potential remains across all three regions.

This chapter adopts the techno-economic perspective to examine how solar cost decline and rising competitiveness have shaped solar PV growth in India. To operationalise cost competitiveness, I adapt the concept of grid parity, treating it as a dynamic phenomenon that evolves over time, varies across states, and differs for two key social actors involved — solar developers and DISCOMs. This framing serves two purposes. One, it clarifies the role and financial exposure of solar developers and state distribution companies. Two, it enables an evaluation of past policies to assess whether they have placed solar on a trajectory of self-sustaining growth.

To this end, this chapter is organised into four main sections. Section 5.1 operationalises different levels of solar competitiveness and outlines their hypothesised effects on solar growth and actors' responses. Section 5.2 tests these hypotheses for technology growth, while Section 5.3 tests the hypotheses regarding actors' response. Finally, in Section 5.4, I synthesise the key findings.

5.1 Types of cost-competitiveness

I operationalise solar cost decline using methods in Section 3.2.2, and observe its changing competitiveness in three steps. First, I lay out the four main features of grid parity, which I use to define different types of cost competitiveness or parity points. Second, I provide a brief overview of solar in India's power sector to highlight the relevant costs and prices used to define these parity points. Finally, I lay out their hypothesised effects on technology growth and actors' response.

5.1.1 Four essentials when defining cost-competitiveness

In the adoption of RE technologies, achieving grid parity has been considered a "holy grail" (Munoz et al. 2014), or "chasm" (Yang 2010), or positive "tipping point" (Breyer and Gerlach 2013; Nijsse et al. 2023), after which technology growth accelerates. At its core, grid parity defines the relationship between the cost of producing RE electricity and various other electricity prices in the market. Despite the simplicity of the concept, a single universal definition, and thus a universal method of quantifying it, remains absent (Breyer and Gerlach 2013; Choi et al. 2015; Olson and Jones 2012; Wang et al. 2025). See detailed discussion in Section 3.2.2. Yet, four main features stand out.

First, grid parity **involves a price or cost equal point**. This may be relative to the cost and prices of targeted RE source versus retail, or wholesale electricity price (Wang et al. 2025), or the cost of generating electricity from other existing sources (Olson and Jones 2012; Yan et al. 2019). For example, Lund (2015) defines grid parity as the point at which "the price of new energy is equal to that of traditional energy. . . without taking account of possible customer preferences." A grid parity definition may also be linked to specific manufacturing or component cost benchmarks, such as the cost of silicon, module, and balance of system costs, or total manufacturing costs, reaching certain thresholds. See Yang (2010).

Second, grid parity **includes a temporal dimension**, referring to the specific point in time when it is achieved. Yan et al. (2019) described it as the tipping point of cost-effectiveness, "when it can be ensured that solar PV power generation is competing with conventional power supplies." This aspect is closely tied to the learning and experience curve in technology diffusion, with origins traced back to Wright (1936). Therefore, some see grid parity as a milestone on the learning curve (Breyer and Gerlach 2013; Munoz et al. 2014), while others view it as a point on the technology diffusion curve (Yang 2010). Either way, reaching grid parity entails that the technology has crossed a "holy grail", after which its adoption accelerates. Previous studies estimated that solar would reach grid parity in most of the Global North countries between 2013-2020 (Bhandari and Stadler 2009; Karneyeva and Wüstenhagen 2017; Spertino et al. 2014). By 2014, 19 countries had already reached the mark (Adeyemi-Kayode et al. 2023).

Third, grid parity **can be interpreted from an actor's perspective**, either implicitly or explicitly, indicating who benefits from reaching this level of cost decline. An implicit example would be — when considering manufacturing cost benchmarks for solar modules, a power developer or component manufacturer might benefit (Yang 2010). An explicit example comes from Yan et al. (2019), who distinguishes between plant-side grid parity (from utilities' perspective for large-scale installations) and user-side grid parity (from households or consumers' perspective for smaller, prosumer[36]-scale systems). See also Munoz et al. (2014).

[36]"Prosumers are agents that both consume and produce energy..." They are mainly "...small and medium-sized agents using solar photovoltaic panels, smart meters, vehicle-to-grid electric automobiles, home batteries and other 'smart' devices..." (Parag and Sovacool 2016)

Finally, grid parity **has a geographic aspect**, indicating where it is achieved. Most analyses use the concept at a national level, but studies at the city or regional level also exist (Biondi and Moretto 2015; Breyer and Gerlach 2013; Choi et al. 2015; Karakaya et al. 2015; Karneyeva and Wüstenhagen 2017; Yan et al. 2019). A higher level of aggregation often hides geographic differences. For example, differences in geophysical characteristics, infrastructure availability, and local policy environments mean that grid parity may occur at different times and stages of technology development, across space. For example, regions with more sunlight, stronger wind resources, or supportive policies might reach grid parity faster than others. Whereas regions with higher potential of competing energy sources may reach grid parity later. See also Munoz et al. (2014).

5.1.2 Types of cost-competitiveness in the Indian solar context

Figure 5.1 shows a simple illustration of energy and monetary flows within the Indian electricity market. The system involves power developers generating electricity and selling it to state distribution companies. DISCOMs then supply electricity to various consumer segments, such as households, industries, and agricultural users. Most DISCOMs are publicly owned and operate across multiple districts within a state. After the 2003 Electricity Act[37], a few privately owned distribution companies have emerged (Chattopadhyay et al. 2023; Vardhan et al. 2024), yet their market share in total electricity supply remains low[38]. Since 2003, India's open access regulations have allowed large consumers to bypass DISCOMs, either buying electricity directly from power developers or generating electricity for captive consumption[39]. These consumers interact with the grid under different business models, paying transmission fees set

[37] The 2003 Electricity Act is the landmark reform introduced to reform the power sector. Key aspects included the separation of businesses engaged in electricity generation, transmission, and distribution, the inclusion of more privately owned companies, the implementation of open access, and captive consumption. Open access enables electricity consumers to procure electricity directly from distribution and transmission networks, without having to rely on distribution companies. (Rustagi and Chadha 2020)

[38] As of 2024, Private DISCOMs account for 5% of the total electricity supply (Josey et al. 2024).

[39] Electricity generation is locally consumed. For example, in India, large consumers install power projects for their personal consumption. As of 2023, captive generating companies account for 15% of the total electricity supply. Lately, commercial and industrial (C&I) consumers have invested in directly buying power from these companies (Josey et al. 2024).

by regulators, all of which vary across states, yet were found to have no impact on state-level differences in solar growth (Shrimali et al. 2020).

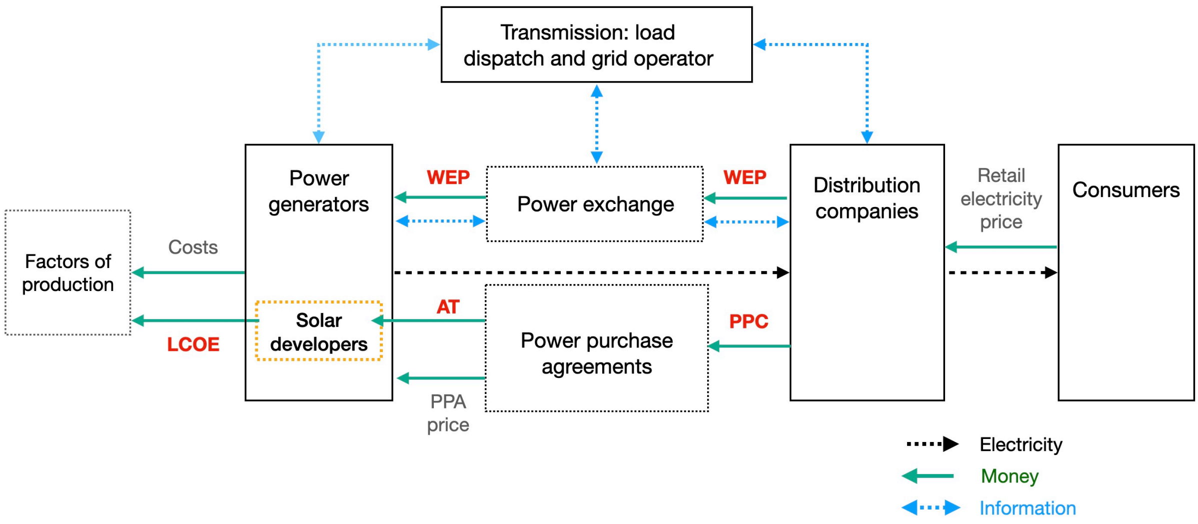

Figure 5.1: Simplified overview of the operations of the Indian electricity market.
Inspired by (Vardhan et al. 2024). The costs and prices used in this dissertation's analysis are shown in red.

In terms of monetary flow, power developers incur costs to generate electricity, including expenses related to technology or fuel, hardware, and balance of system components, operations and maintenance, financing, land acquisition, permitting, and research and development. Developers are compensated through negotiated prices, typically established via auctions for solar developers and formalised in long-term Power Purchase Agreements (or PPAs) with DISCOMs, or other intermediary off-takers[40]. Most other power developers also rely on long-term PPAs based on strict take-or-pay principles[41] (Kumar et al. 2022). A small portion of electricity is traded in power exchanges, (Chattopadhyay et al. 2023), where prices are determined based on demand and supply. Christophers (2024) (p.238) notes that this quantity traded is mostly excess generation above what is contracted in PPAs. DISCOMs, thus, can buy electricity directly from developers at negotiated tariffs, or through power sale agreements with intermediate pro-

[40]Off-takers are those that contract to purchase electricity from power developers.
[41]The take-or-pay principle states that the electricity procurer must either buy the minimum amount of electricity contracted, based on the PPA, or pay for it.

curers[42], or on the power exchange at the market price, to meet electricity demand. DISCOMs then sell this electricity to consumers at regulated retail prices, which are shaped by political decisions (Chattopadhyay et al. 2023). Aspects at the retail level are beyond the scope of this dissertation. All costs and prices at the wholesale level exclude service taxes, infrastructure usage fees, transmission losses, wheeling charges, and benefits from power banking regulations.

Against this backdrop, to define solar cost-competitiveness, I look at four cost and price indicators based on methods in Section 3.2.2. See costs/prices (in red) in Figure 5.1. The **Levelised Cost of Electricity (or LCOE)** represents the techno-economic cost solar developers must incur to produce electricity in a year. The **Wholesale Electricity Price (or WEP)** reflects the weighted average price of electricity from all energy sources traded in the power exchange in a year. Kumar et al. (2022) notes that exchange prices are about 12% higher than PPA tariffs in bilateral contracts, making WEP a reasonable proxy for electricity prices at the wholesale level. The weighted average **Auction Tariffs (or AT)** discovered through solar auctions show the selling price of new installations for solar developers, or the marginal cost of contracting new solar capacity for DISCOMs, in a year. The weighted average **Power Purchase Costs (or PPC)** captures the real cost DISCOMs pay in a given year to procure power from different energy sources, including solar, coal, large hydro, nuclear, and wind. In other words, while AT captures the immediate market or policy-driven changes in the cost of producing solar electricity, PPCsolar reflects the cumulative costs DISCOMs incur from all existing solar contracts. So, for example, the effect of declining technology costs is not immediately visible in DISCOMs' PPC. Their annual spending depends on the tariffs of past and present contracts, the share of capacity tied to those contracts, and the time it takes for new installations to become operational.

[42]This is applicable, e.g., for solar contracted by the national-level off-taker SECI (Rustagi and Chadha 2020).

5.1.3 Cost-competitiveness and corresponding hypotheses

I identify four potential parity points, each reflecting growing solar cost competitiveness. Parity points are calculated annually for a given year *t*. When viewed from the perspective of solar developers, cost-competitiveness can be defined in relation to the costs developers incur to produce solar electricity, the price they can sell it to DISCOMs, and the market price of electricity on the grid. From this, two types of parity points emerge. I refer to them as 'developers parity' (D-parity) and 'cost parity' (S-parity).

(i) **D-parity** is achieved when $\text{LCOE}_t \leq \text{AT}_t$, or when the cost of generating solar electricity is equal to or lower than the price at which developers can sell electricity to the grid.

(ii) **S-parity** is achieved when $\text{LCOE}_t \leq \text{WEP}_t$, or when the cost of generating solar electricity is equal to or lower than the wholesale electricity price in the market.

When viewed from the perspective of DISCOMs, cost-competitiveness can also be defined in relation to the auction tariff, the market price of electricity, and the power purchase costs from solar and other energy sources. Here too, two types of parity points emerge, which I refer to as 'price parity' (U-parity) and 'cross-source parity' (C-parity).

(iii) **U-parity** is achieved when $\text{AT}_t \leq \text{WEP}_t$, or when DISCOMs can contract new solar at a price equal to or lower than the wholesale electricity price in the electricity market.

(iv) **C-parity** is achieved when $\text{PPCsolar}_t \leq \text{PPC(coal/wind/nuclear/hydro)}_t$, or when DISCOMs' average cost of buying all contracted solar electricity is equal to or lower than the average cost of buying electricity from other contracted energy sources.

Table 5.1 summarises the anticipated effect of achieving each type of parity on technology growth and actors' response. That is, on developers' ability to install new solar capacity, and on DISCOMs ability to procure new capacity through solar auctions. D-parity and S-parity are defined from the perspective of solar developers, as they are linked to the cost of producing solar electricity. I assume developers, who are generally privately owned entities, act as rational economic agents (Steffen et al. 2022). They seek D-parity as a baseline condition for investment, bidding tariffs above production costs to ensure profitable returns. Achieving D-parity may not itself accelerate growth, since it primarily lowers tariffs through competition rather than expanding adoption. By contrast, achieving S-parity — where solar production costs fall below the electricity price at the grid — represents a transformative milestone. It signals that, on average, solar is cheaper to produce than buying electricity from major alternatives. This creates strong incentives for developers, attracting more investment and accelerating adoption. DISCOMs, however, may respond differently to these parity points. D-parity offers them little benefit, as early solar projects often remained more expensive than conventional power. In such cases, DISCOMs contract solar primarily due to policy mandates rather than economic advantage. This is seen in Gujarat, where solar was procured at much higher prices than coal-based electricity to promote early adoption (Busby and Shidore 2021). High tariffs may attract developers but discourage DISCOMs from contracting large volumes, due to the risk of long-term financial burdens. In contrast, S-parity will strongly incentivise DISCOMs. Once solar is cheaper than other sources, DISCOMs will have a direct financial motive to contract more solar at tariffs below the WEP, expand auctions to maintain their consumer base, and also invest in enabling infrastructure such as storage and grid upgrades.

U-parity and C-parity are defined from the perspective of DISCOMs, as they capture the costs of signing new contracts or procuring solar electricity across off-takers' portfolios. DISCOMs are not purely profit-driven. As public-owned entities, their operation is often shaped by government interests and directives (Steffen et al. 2022). As exemplified in the previous example from Gujarat, in the early stages of adoption, DISCOMs were ordered by the then state government to sign solar contracts at prices much higher than cheaper conventional energy sources (Busby and Shidore 2021). Thus, achieving U-parity would mark a turning point. It

Parity type	Short definition	Hypothesised actors behaviour	Hypothesised effect on growth
D-parity LCOE ≤ AT	Developers' parity	Developers cover costs & gain profits → invest. During high solar costs, DISCOMs may contract solar (due to purchase obligations) but limit engagement.	Potential limitations in growth
S-parity LCOE ≤ WEP	Cost parity	Consumers prefer developing solar over grid purchase → demand rises → developers invest. DISCOMs prefer solar contracts over grid purchase → demand rises → developers invest.	Strong growth
U-parity AT≤ WEP	Price parity	DISCOMs run more auctions → demand rises → developers invest.	Strong growth
C-parity PPC (solar) ≤ PPC (coal/hydro/ nuclear/wind)	Coal/ Hydro/ Nuclear/ Wind parity	DISCOMs gain financial room → demand for solar rises → developers invest.	Strong growth

Table 5.1: Parity type, and hypothesised changes in actors' behaviour and technology growth.

would mean that hereon, new solar contracts are cheaper than new contracts from other energy sources, which would encourage DISCOMs to expand auctions and procure larger solar capacities. C-parity would also be a strong milestone, occurring when the average cost of all contracted solar (including legacy contracts) falls below the cost of conventional electricity (also including legacy contracts). This not only frees financial space for DISCOMs but also strengthens their long-term viability, making solar procurement more attractive and financially sustainable. Both U-parity and C-parity would drive solar adoption by increasing DISCOMs' willingness to contract new solar, thereby creating higher demand for developers. For developers, this means larger market opportunities but also fiercer competition and downward pressure on tariffs as participation broadens.

5.2 Cost competitiveness and technology growth

I map the evolution of costs and prices and the corresponding changes in technology growth in two steps. First, I analyse the temporal and spatial evolution of the four cost and price indicators. Next, I identify when and where the four parities are achieved, mapping corresponding changes in technology growth.

5.2.1 Temporal and spatial patterns in cost-competitiveness

The Levelised Cost of Electricity (LCOE) represents the cost developers incur to produce solar electricity. It is defined in two complementary ways. First, as the present value of the total cost of generating solar electricity over a project's lifetime (NREL 2024). Second, as the break-even price at which electricity must be sold over the project's lifetime while earning a return on investment equal to the discount rate (NREL 2024). Figure 5.2 (panel a) shows the evolution of solar LCOE as the weighted-average cost in 2023 USD/kWh. I calculate LCOE using methods in Section 3.2.2. Over time, strong policy support drove sharp cost reductions in solar technology, which translated into steep declines in LCOE worldwide (Nemet 2019). National LCOECal aligns closely with IRENA's estimate for India, but remains higher. I attribute this difference to potential missing project-level data for all Indian states in IRENA's database[43], and/or different Capacity Utilisation Factor (CUF) assumptions between LCOEIrena and LCOECal. The former consistently aligns with the lower bound of state-level LCOECal, reflecting either a stronger representation of projects from high-performing states or systematically higher CUF assumptions for Indian solar projects.

Two main trends characterise the evolution of LCOE over time and space. First, solar costs have fallen dramatically. Between 2010 and 2023, LCOE declined by 87%. Yet, most of this decline occurred before 2018. After 2018, cost reductions slowed, and in the last two years, costs increased due to supply chain disruptions – first from COVID-19 lockdowns (IEA 2020b) (p.11-19), and later from polysilicon shortages (IEA 2022). LCOE has closely mirrored solar module prices, which account for nearly half of total CAPEX (IRENA 2020) (p.66). For reference, module prices fell by 85% by 2017, and by 92% by 2023 compared to 2010 (IRENA

[43]Based on email correspondence with IRENA.

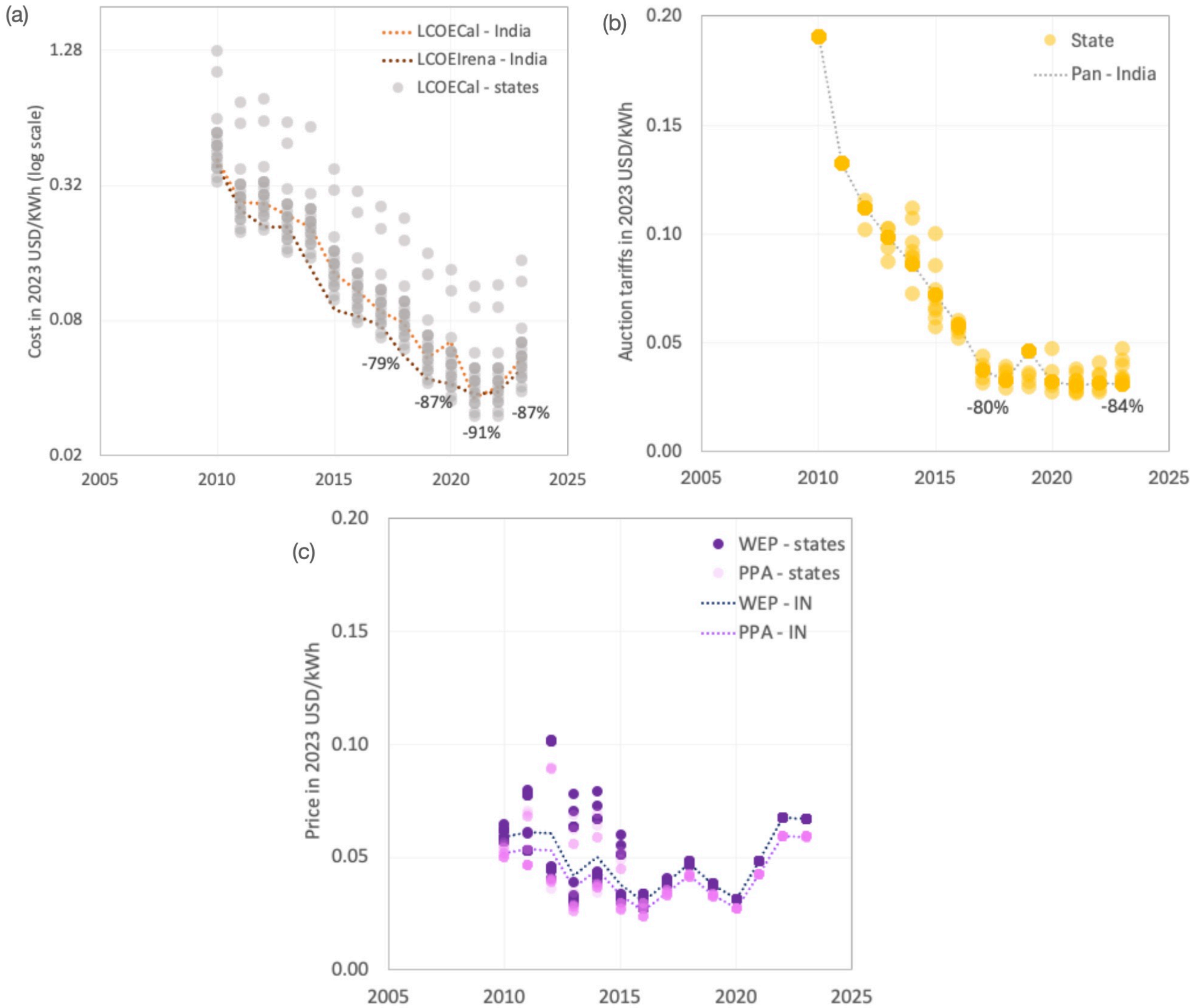

Figure 5.2: Change in various electricity costs and prices between 2010-2023.
Levelised cost of electricity (top left), auction tariffs (top right), and wholesale electricity price (bottom middle). Dots represent state-specific values, while lines show national weighted averages.

2024a). Second, LCOECal varies substantially across states. In 2010, LCOECal ranged from 1.28 USD/kWh in West Bengal to 0.33 USD/kWh in Kerala. By 2022, LCOECal dropped to 0.04 USD/kWh in Kerala and Rajasthan, compared to 0.15 USD/kWh in West Bengal. These differences reflect not only differences in solar irradiance but also how effectively installed capacity is converted into generation across states. For instance, Gujarat, Maharashtra, and Madhya Pradesh experience lower CUF despite high irradiance due to grid curtailment. See table 3.1 and Figure A.8 in the appendix. While auction clauses protect developers from direct financial losses (Rustagi and Chadha 2020), curtailment reduces the realisation of solar potential (Rao and Agarwal 2021) and raises policy costs through stranded assets (Shrimali et al. 2020).

Figure 3 (panel b) illustrates the evolution of weighted average AT at state and pan-India auctions, showing a trajectory tightly aligned with LCOE. Auction tariffs remain highly responsive to cost developments. Between 2010 and 2023, AT fell by 84%, again with most reductions occurring before 2018. In recent years, AT rose modestly, mirroring rising costs due to supply-side constraints. However, since 2018, AT has stabilised, unlike LCOE. I attribute this to policy changes at the time. The introduction of import taxes in 2018 (discussed further in Section 6.3) offset technology cost reductions, reducing developers' incentives to underbid. See figure A.13 in the Appendix. Beyond policy, this stabilisation may also reflect broader market dynamics. As RE prices converge with WEP, there is little motivation for developers to underbid and lose out on potential profits.

In panel (c), WEP reveals initial heterogeneity across states that diminished over time, leading to price synchronisation from 2017. This synchronisation results from the exclusion of transmission losses in day-ahead market calculations, under the assumption of an uncongested system. Congestion is resolved by the national system operator through market-splitting and residual capacity transfers, producing some bid-area price differentiation (Chattopadhyay et al. 2023). Overall, WEP has remained relatively stable, fluctuating between 0.03–0.10 USD/kWh from 2010 to 2023. Assuming PPA tariffs at 12% below WEP, these ranged between 0.02–0.09

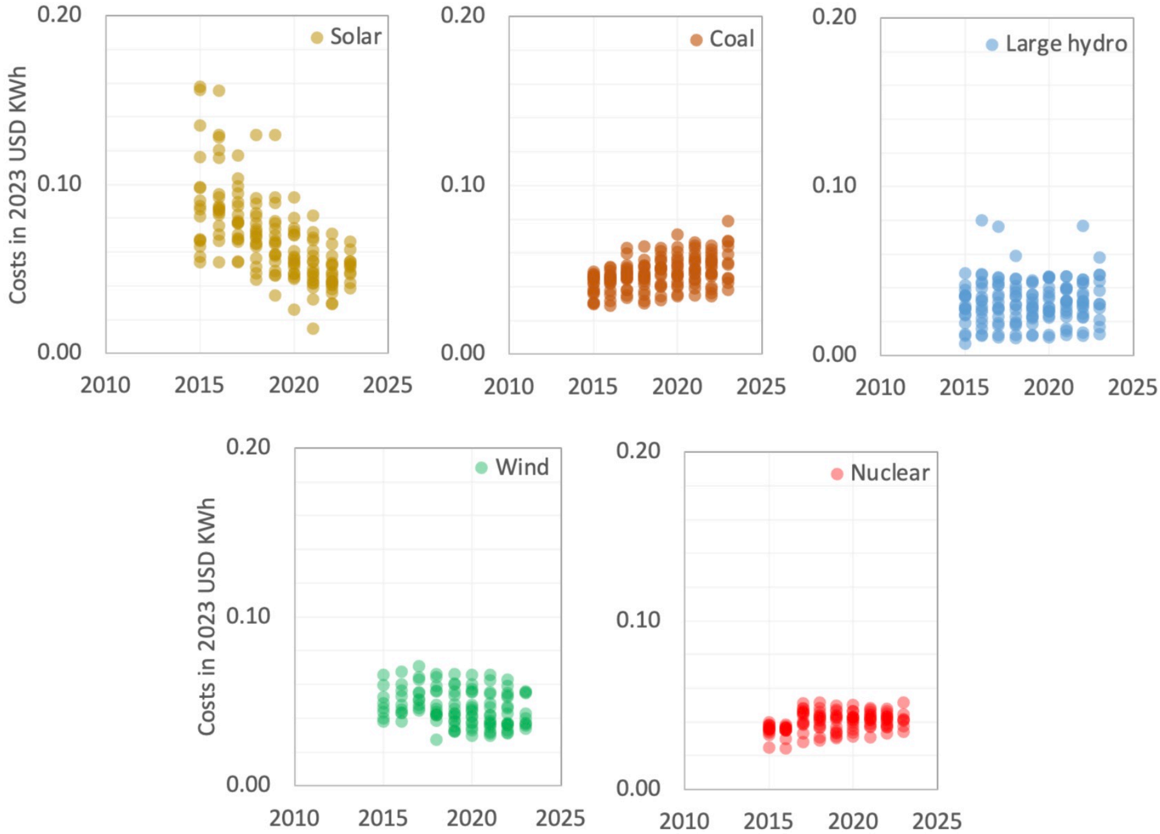

Figure 5.3: Change in Power Purchase Costs borne by state DISCOMs
Dots are state-specific values.

USD/kWh. The early heterogeneity was primarily driven by higher WEP in southern states.

Finally, Figure 5.3 shows the weighted average PPC paid by DISCOMs, reflecting the revenues of power developers (inclusive of legacy contracts), segmented by energy source — solar, coal, large hydro, wind, and nuclear. PPC for mature technologies has remained stable, with inherent cost differences across sources. By contrast, solar PPC declined sharply as falling tariffs and lower technology costs passed through to DISCOMs. This reflects the long-term nature of PPAs. AT reflects the marginal cost of new solar, not the costs DISCOMs actually pay at a given time. For instance, although AT had dropped to 0.07 USD/kWh by 2015 (Figure 5.2, panel b), many DISCOMs remained locked into older, more expensive contracts, pushing average PPC up to 0.16 USD/kWh in 2015 (Figure 5.3, panel solar), and illustrating the financial rigidity of long-term PPAs. DISCOMs remain bound by past purchase agreements even as technology market prices fall. Over time, as legacy PPAs expire and are replaced by lower-cost contracts, the weighted average PPC for solar is likely to converge with auction tariffs and stabilise.

5.2.2 Changes in cost-competitiveness and technology growth

Figure 5.4 shows the evolution of LCOE, AT, WEP, and annual capacity additions at the national level, and Figure 5.5 shows the same at the state and regional level.

D-parity is not achieved throughout the studied period. If developers are rational, profit-driven actors, this outcome contradicts that assumption, demonstrating that auction tariffs do not fully cover costs. The outcome points to two implications. First, it signals that policy support is still needed to retain solar profitability in India, even though the level of that support and the profit margin remain unknown. In other words, the true cost of installing solar from a developer's perspective, including their profit margins over time, is opaque. Equally unclear is the actual level of policy support they receive[44]. For instance, while LCOECal reflects the true capacity

[44] Incorporating policy support based on methods in Figure A.2 did not change this outcome. Similarly, incorporating land costs made the difference between LCOE and AT bigger. See Figure A.3

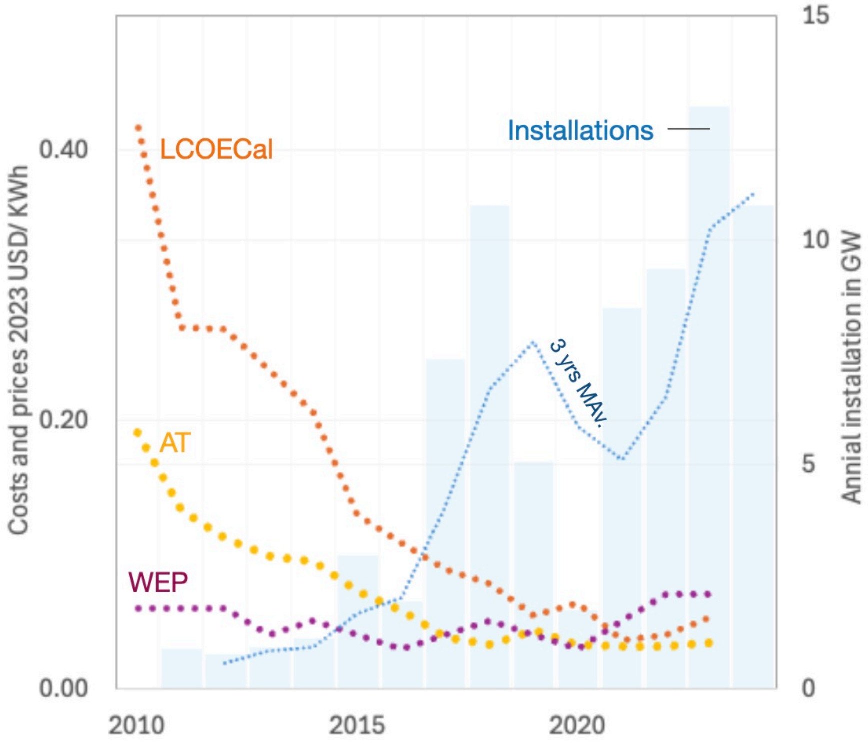

Figure 5.4: Achievement of different types of cost-competitiveness at the national level. *Price parity (U-parity) is achieved in 2017, when auction tariffs equal the wholesale electricity price. Cost parity (S-parity) is reached in 2021, when the levelised cost of electricity equals the wholesale electricity price.*

utilisation factor (CUF), developers remain financially shielded from curtailment. In reality, lower CUF due to curtailment raises costs covered by policymakers. Thus, the difference between LCOE and AT potentially entails the policymakers' burden. Yet, the incentive for private developers, essentially profit-maximising agents, remains unknown[45]. A second plausible explanation is that developers prioritise market share over immediate profits (discussed further in Section 5.3.1). In either case, current research leaves gaps in understanding both developer costs and the magnitude of policy effort required to sustain solar PV as it transitions from an emerging to a mature technology. Because of these cost uncertainties, the implications of the missing D-parity for deployment remain unresolved.

U-parity — when developers can sell solar electricity at or lower than wholesale electricity prices (WEP), or DISCOMs can sign solar contracts at prices comparable to other sources — was achieved in 2017 (Figure 5.4). In southern states, AT approached WEP earlier, but full equivalence occurred only in 2017. This reflects higher electricity prices in the south, largely due to low coal availability in the region. Consistent with this, in Figure 5.6, C-parity also occurred earlier in the south. Solar broke-even with coal and wind in 2019, compared with 2021 nationally. In the north-east, solar reached parity with coal in 2021 and briefly with large hydro in 2022, while in the north-west, solar matched wind in 2021 but not coal within the study period. In contrast, U-parity was reached simultaneously across states, driven by the introduction of pan-India auctions in 2018, which were not state-centric and theoretically allowed capacity installations anywhere in the country (MNRE 2017).

[45]Interestingly, shifting AT forward by two years aligns it with IRENA's LCOE estimates, which are also techno-economic in nature. Although correspondence with IRENA suggests this alignment is coincidental, it underscores the lack of transparency around actual project costs and the extent of policy effort directed toward solar deployment.

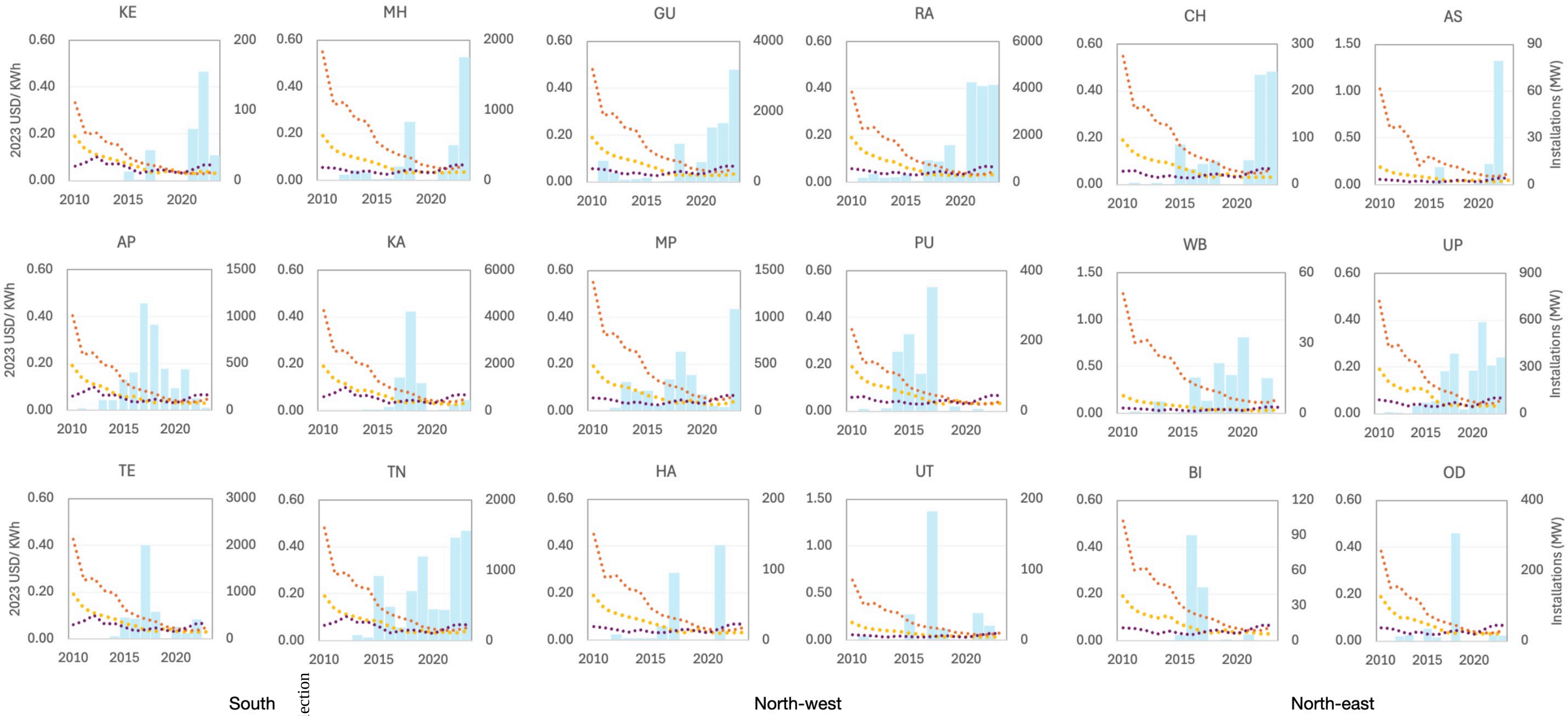

Figure 5.5: Achievement of different types of cost-competitiveness at the state level.
Cost and price parities are achieved simultaneously across all states.

Yet, neither U-parity nor C-parity translated into sustained solar acceleration. The national acceleration phase after U-parity was abruptly slowed down in 2019 with the introduction of import taxes on solar modules. In 2020, this persisted due to COVID lockdowns. Although growth resumed in 2021, the earlier pace of acceleration was not restored, as solar continued to grapple with global supply chain disruptions. Regionally, the slowdown was brief in the north-west but prolonged in the south and north-east. Similarly, C-parity did not consistently trigger growth. While national C-parity with coal in 2021 coincided with expansion, regional patterns diverged. In the north-west, Gujarat and Rajasthan led growth post-parity. In the south, Maharashtra and Tamil Nadu drove adoption despite earlier stagnation, but growth in early adopters stalled. In the north-east, Chhattisgarh, Assam, and Uttar Pradesh grew while others slowed, leaving overall regional growth unchanged. These variations challenge the assumption that achieving price and cross-source parities lead to sustained RE acceleration. Clearly, regional patterns here point to non-cost mechanisms at play.

Finally, S-parity, i.e., when LCOECal fells below WEP, enabling developers to profit from direct market sales or self-consumption, was reached nationally in 2021, with similar patterns across states. Only exceptions were the north-eastern states of Assam and West Bengal, where S-parity was not achieved within the studied period. Yet, solar has recently started to accelerate in West Bengal. Achieving the S-parity milestone signals solar's rising competitiveness to the point where auctions may no longer be required. It also underpins a major shift toward captive consumption, especially in the commercial and industrial (C&I) sector, where installations tripled in 2022. See Figure 5.8, panel C&I consumers. Growing adoption of open access reflects solar's capacity to bypass DISCOMs, echoing U.S. and EU trends in the late 2010s when falling renewable costs fuelled concerns over a utility 'death spiral.' As consumers shifted to self-generation, utility revenues declined, triggering higher prices and further migration (Athawale and Felder 2022; Castaneda et al. 2017; Laws et al. 2017). In India, where DISCOMs are already financially fragile, this dynamic could be counterproductive. Yet, it remains unclear whether a utility death spiral is a real threat overall and if India is approaching

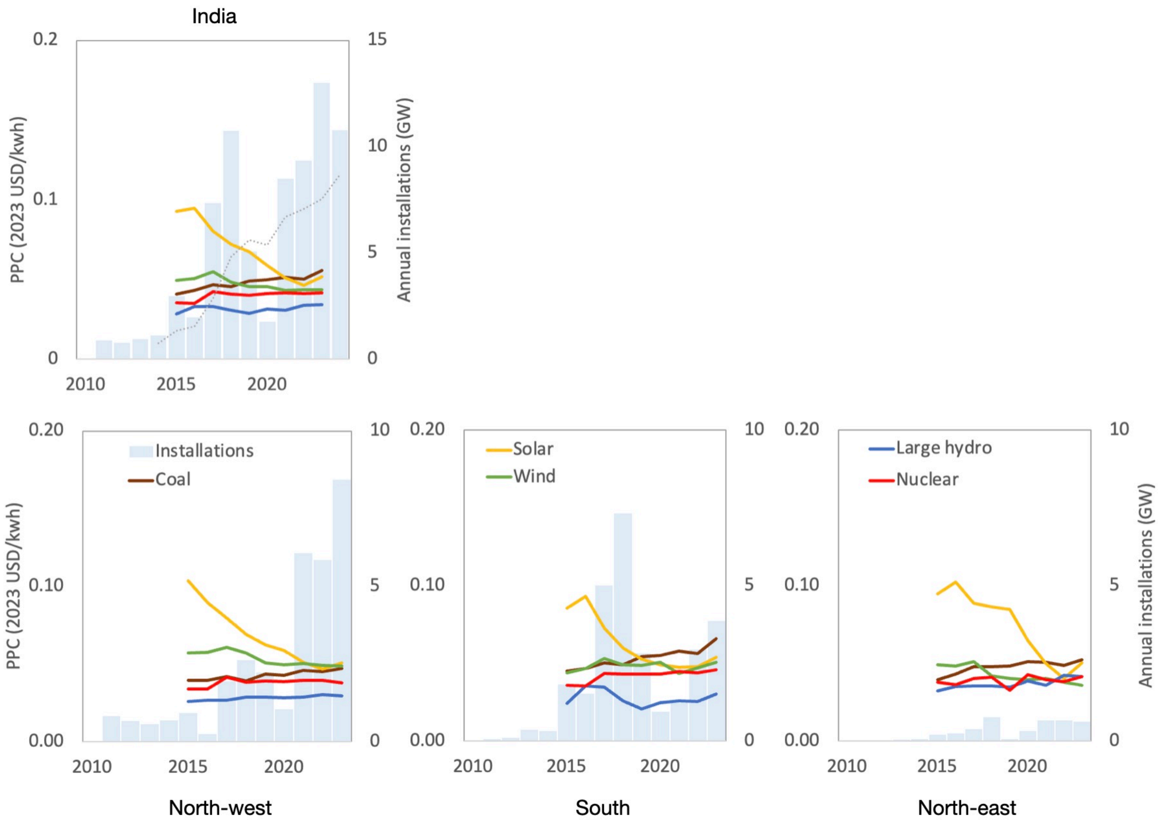

Figure 5.6: Achievement of cross-source parity at the national (top) and regional levels (bottom).

Solar achieves cross-source parity (C-parity) with coal in 2021 nationally and in the North-east, and in 2019 in the South. Solar also reaches C-parity with wind energy, but this is not consistent, as rising solar PPC in 2023 prevents lasting competitiveness.

one (Martin 2023; Tongia 2014). Nevertheless, the findings here underscore the insufficiency of cost decline alone to sustain technology acceleration. Crucially, as with U- and C-parity, S-parity does not consistently translate into deployment growth. Instead, the relationship reflects different regional patterns, as previously discussed, rather than being purely driven by economic signals.

5.3 Developers' and DISCOMs' response to cost-competitiveness

How did key social actors respond to the solar cost decline and its rising cost competitiveness? Solar developers and DISCOMs play distinct roles in scaling utility-scale solar adoption. Developers build solar power plants and sell electricity, while DISCOMs procure this electricity through auctions or power sale agreements with intermediaries like SECI, ultimately supplying it to consumers. As solar costs declined and competitiveness grew, both actors' capacities evolved. Ideally, developers could build more projects, and DISCOMs could more effectively procure solar power through auctions. In this section, I explore how reaching different parity points influenced these actors' ability to perform their respective roles, thereby driving solar growth. While state-level granularity was not feasible for tracking developers' activity [46], this detail is maintained when discussing DISCOMs.

5.3.1 Cost-competitiveness and developers' response

Developers-parity, or D-parity, is not achieved. In other words, given the available cost information, developers on average consistently bid tariffs below LCOECal, implying sustained losses or dependence on policy support, the full extent of which remains uncertain. The first explanation — that profit-driven private developers willingly accept losses — may seem counterintuitive. A more plausible interpretation is strategic: developers deliberately sacrifice short-term profitability to secure market share. By doing so, larger players achieve economies of

[46] Mapping developers' state-level engagement could offer further insights and could be a scope for future research.

scale, reduce future costs, and strengthen their ability to influence solar electricity prices, ultimately positioning themselves for long-term profitability. To test this hypothesis, I examine over 90 solar developers and their evolving market shares from 2009 to 2023 based on commissioned capacities, using methods from Section 3.2.3. The analysis reveals that developers can be grouped into distinct categories according to their final 2023 market shares, with each category showing distinct responses to cost declines and parity achievements. These responses shape not only their positioning but also their role in driving solar adoption over time.

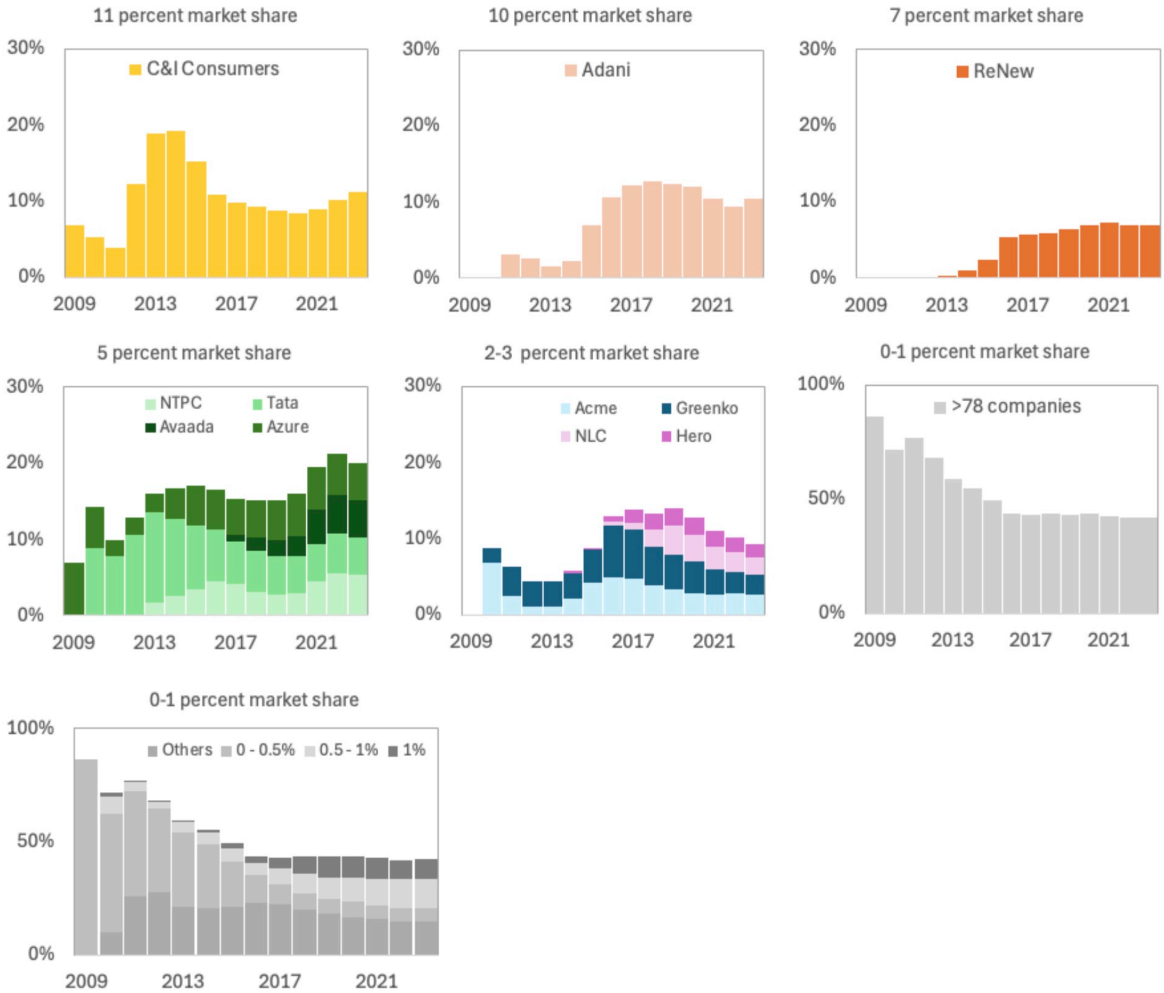

Figure 5.7: Changing market share of key solar developers between 2009-2023.
Solar developers are grouped based on their market share as of 2023.

Figure 5.7 shows a clear trend of market consolidation. Smaller developers — particularly those holding less than 1% market share — steadily lost ground, while a handful of larger players (six firms in the 10%, 7%, and 5% categories) expanded and entrenched their dominance. By 2023, these firms collectively controlled nearly half of the market. The bulk of this reshuffling occurred before 2018, coinciding with the achievement of U-parity and the subsequent stabilisation of auction tariffs (see Figure 5.4, panel b). This reshuffling phase overlapped with rapidly falling tariffs, which squeezed out smaller firms. Larger developers leveraged their financial capacity, risk appetite, economies of scale, and in many cases prior experience in the power sector (e.g., Tata Power, NTPC) — capitalised on this moment. Their access to low-cost capital allowed them to place aggressive bids in increasingly competitive auctions, consolidating market share as smaller firms exited. By contrast, after 2017, once tariffs stabilised, the churn between large and small players ceased. Yet, competition persisted within the larger categories, where new entrants (such as NCL, Hero, Avaada) expanded their positions at the expense of some early adopters. From this stage onward, clear market leaders emerged — most prominently Adani Group and ReNew Power.

The post-U parity period saw another round of market reshuffling, though less intense than before. Larger developers, particularly those in the 10%, 7%, and 5% brackets, proved resilient. Despite being early adopters, they successfully navigated tariff declines and rising costs. Even when import duties, COVID-19 disruptions, and supply shortages temporarily raised costs, these firms not only preserved their positions but in some cases expanded them. Adani, for instance, rebounded strongly after scaling back, while ReNew Power continued installations without interruption. That said, most firms felt the burnt of rising costs. Market acceleration after 2020 was led by NTPC — a government-backed thermal power producer diversifying into renewables — and Avaada, which leveraged its manufacturing arm to benefit from import tax policies. See Figure 5.8. This coincided with the achievement of C-parity at the national level, where solar PPC reached parity with coal. The shift was pivotal for two reasons. One, a public-owned enterprise (NTPC is the implementing agency of the Ministry of Power), helped stabilise the market during times of external and policy shock. Two, solar's growing competitiveness vis-à-vis coal allowed space for a coal-based utility to expand its renewables portfolio not defensively, but as a profitable opportunity (Pai and Jai Pai and Jai). Meanwhile, smaller developers such as Hero Future Energies and Northern Coalfields Limited (2% category), along with mid-tier players like Acme and Greenko (3% category), struggled to sustain new capacity in the face of cost pressures. Collectively, smaller firms still added the most capacity, but unlike the pre-2017 period, the contributors were no longer the early pioneers — indicating a reshaping of the small-developer segment as well.

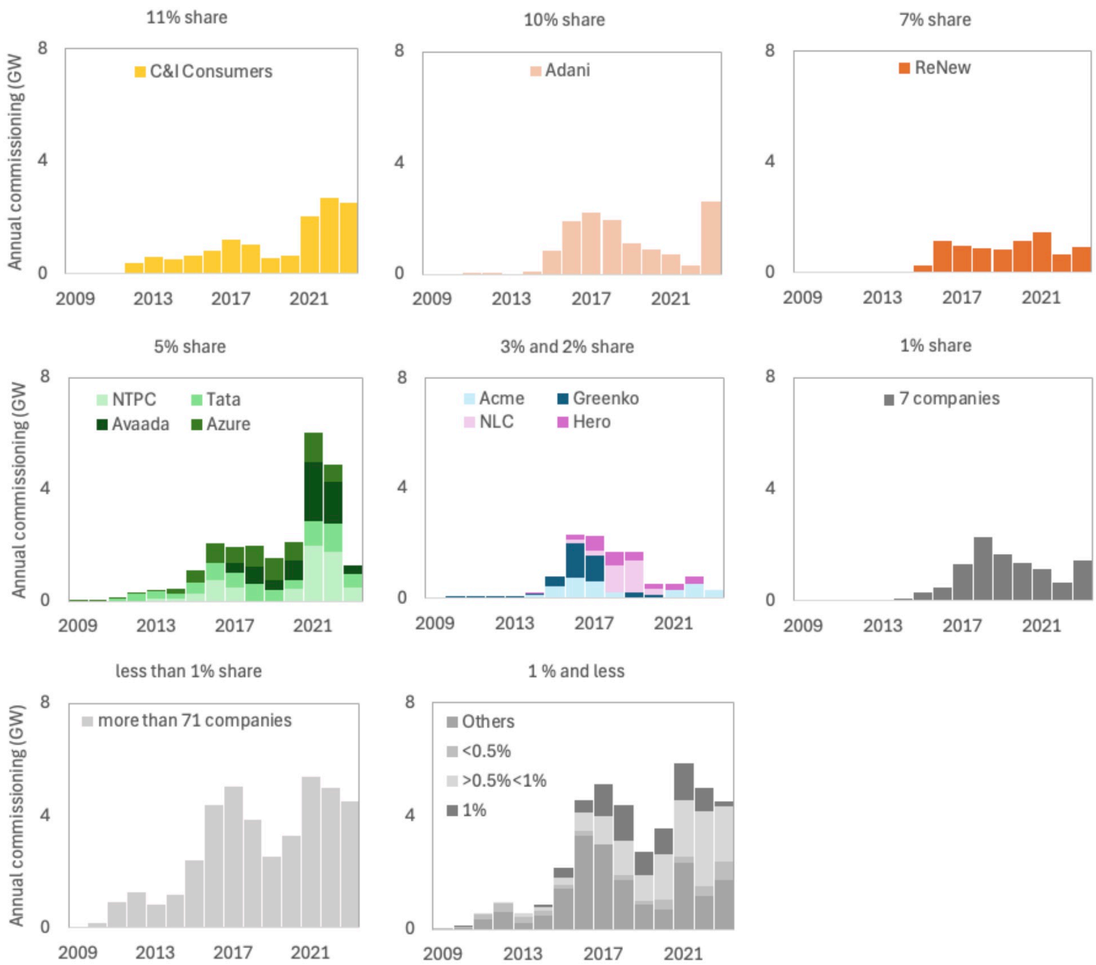

Figure 5.8: Absolute capacity commissioned by different developers between 2010-2023.

Finally, as hypothesised, the achievement of S-parity marked a decisive turning point. Capacity additions by the C&I developer segment expanded sharply. See Figure 5.8. With the LCOE falling below WEP, businesses were incentivised to pursue captive generation, reducing exposure to financially unstable DISCOMs. By 2023, the C&I segment held the largest individual share of commissioned capacity (11%), underscoring the attractiveness and durability of self-generation models. Contrary to expectations of wider participation, market competitiveness did not translate into more new entrants. The surge of new developers occurred primarily during earlier adoption phases, peaking with capacity installation booms in 2012, 2017, and 2021. Yet, the level of new entry after 2017 remained lower than in the formative years of the sector, suggesting barriers to entry have hardened over time. See Figure A.14 in the appendix.

5.3.2 Cost-competitiveness and power procurers' response

Figure 5.9 shows the annual solar capacity auctioned in India, distinguishing between national off-takers and state DISCOMs, and subsequently the regional and temporal variations across states. Until 2017, state DISCOMs dominated auctions, but from 2018 onwards, national off-takers assumed a leading role. DISCOM-led auctions remained relatively stable until 2022, but in 2023, their auctioned capacity rose sharply for the first time. Significant regional differences persist throughout — in the scale of capacity auctioned, the timing of auctions, and which DISCOMs participate. Three distinct periods emerge, aligned with differences in growth patterns and parity achievements.

Until 2013, most capacity additions occurred in the north-west, even though auctions in the region were scarce at the time. In Gujarat, early installations were driven by a feed-in tariff (FIT) model, where the state government compelled DISCOMs to sign solar contracts (Sareen and Kale 2018). Beginning in 2009, developers received compensation as high as 0.25 USD/kWh (2023 equivalent) (Shidore and Busby 2019). Gujarat DISCOMs did not hold auctions until 2017, nearly for eight years, potentially because they remained locked into high tariff contracts. Madhya Pradesh and Punjab registered growth through state-led auctions, but the capacities remained limited. In contrast, Rajasthan's capacity additions were led by not the state, but national off-takers. Thus, deployment in this formative phase was not from auctioned capacity but shaped by policy effort and resource endowment, both of which had a regional focus.

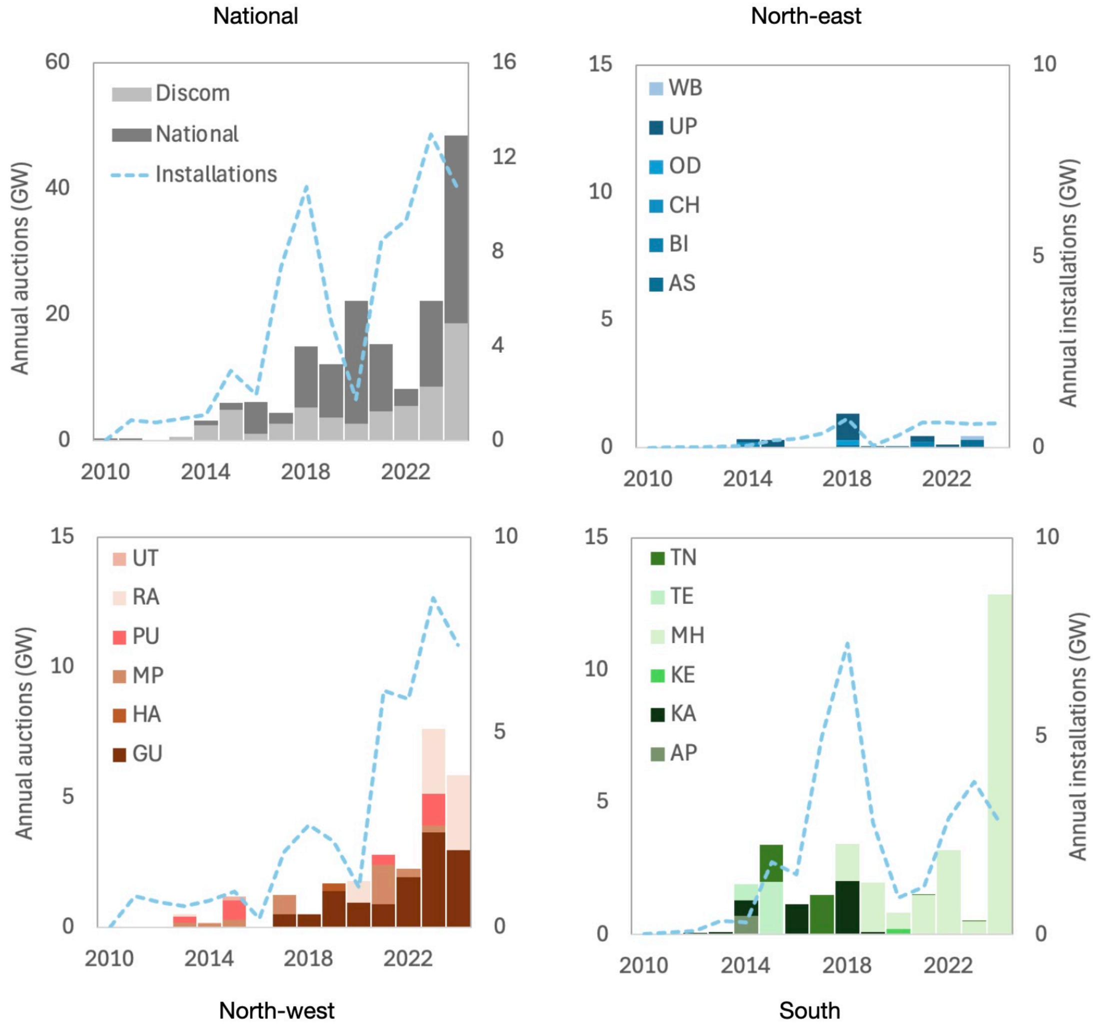

Figure 5.9: Auctions conducted by national and state off-takers between 2010-2024
The blue line represents annual installations for the corresponding national or regional level.

In the first half of the accelerating growth phase (2014–2018), southern DISCOMs auctioned approximately 12 GW of capacity — four times higher than the north-west and six times higher than the north-east. This surge in auction activity drove rapid capacity additions and pushed national growth to a peak in 2018. The momentum, however, was unsustainable. DISCOMs in Andhra Pradesh, Telangana, and Tamil Nadu came under severe financial strain from high-tariff PPAs, which inflated operating costs and constrained their ability to initiate new contracts. Renegotiations of earlier PPAs, delays and non-payment of tariffs, and cancellation of tenders after auctions, became widespread (Prateek 2019b; Shah 2019). Developers' trust eroded, leading to widespread under-subscription of DISCOM-led auctions (see Figure 5.10). As a result, southern DISCOMs' ability to sustain growth collapsed. Their withdrawal after 2018 was decisive: U-parity in 2017, instead of accelerating adoption, exposed structural weaknesses. Higher tariffs had locked off-takers into commitments they could not sustain, undermining their role in driving adoption and tariff reduction. In other words, early mover DISCOMs, instrumental in bringing down tariffs, withdrew from auctioning and technology growth thereafter.

2018 marked a turning point in auction dynamics. National off-taker-led auctions surged, with the Solar Energy Corporation of India Limited (SECI) emerging as the central actor. SECI assumed an intermediary role, signing power purchase agreements with developers and power sale agreements with DISCOMs. This was a deliberate policy intervention from the national government to insulate developers from the investment risks of contracting with financially distressed state DISCOMs (Rustagi and Chadha 2020). Meanwhile, the volume of DISCOM-led auctions held steady, though the composition of active participants shifted. Previously inactive eastern states held a few small auctions, while southern activity remained stable before expanding dramatically in Maharashtra. In the north-west, auction activity steadily increased, led by financially stronger DISCOMs in Gujarat. After 2019, most DISCOM-led auctions were concentrated in Gujarat (12 GW), Rajasthan (6 GW), and Maharashtra (20 GW). Auctions in

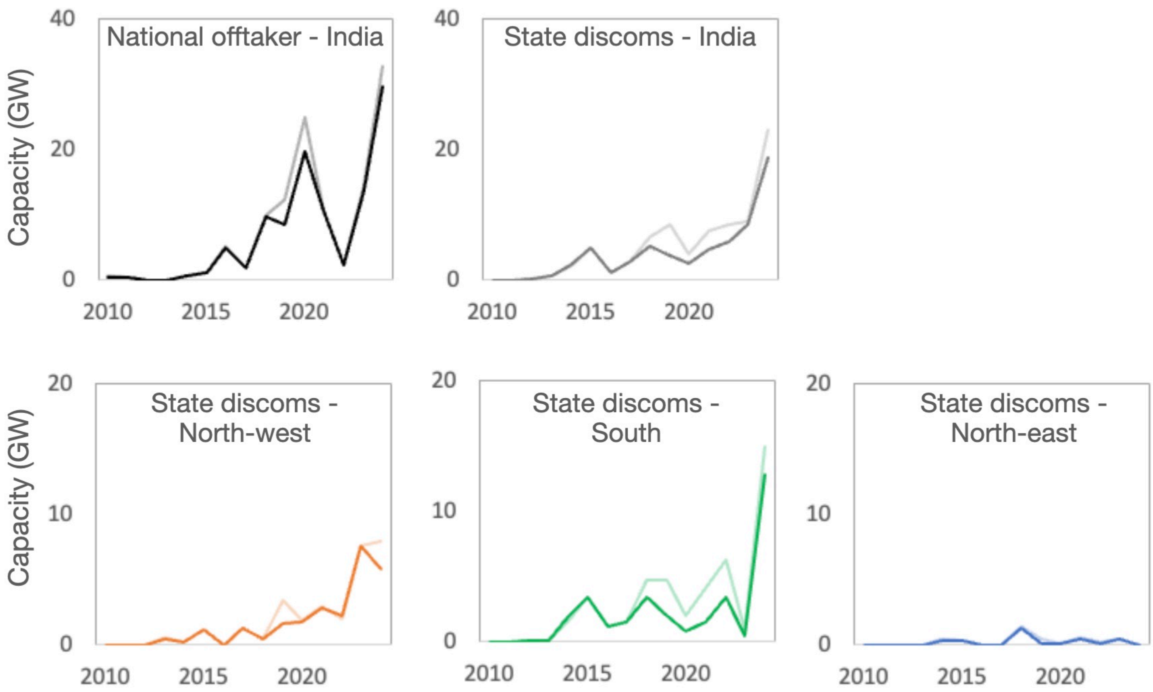

Figure 5.10: Capacity tendered and actually allocated in solar auctions between 2010-2024. *The figure shows how subscription of solar auctions changed annually between 2010-2024. The lighter lines represent the total capacity tendered by each off-taker type, while the darker lines show the capacity that was actually allocated to developers. Allocation depends on developer participation in the auction and whether they reach an agreement with the off-taker on price and capacity. The top row tracks auctions at the national level, first by central off-takers and then by state DISCOMs. The second row breaks down auctions by DISCOMs across different regions.*

Rajasthan and Maharashtra were tied to the agriculture feeder scheme[47], while Gujarat's were linked to the interstate transmission scheme [48].

By 2021, the achievement of C-parity and S-parity may have improved DISCOMs' financial flexibility to sign new contracts and provided an incentive to compete against the rising captive consumer market. Yet, their role in driving growth during this period remains ambiguous for two reasons. First, the impact was uneven across DISCOMs. Second, policy measures continued to shape outcomes. Nearly half of the auctioned capacity during this period fell under the agri-feeder scheme, which subsidised developers to install distributed solar while enabling DISCOMs to purchase excess generation (MNRE 2025b). This scheme was concentrated in Rajasthan and Maharashtra. The UDAY bailout (2016–2017) temporarily eased DISCOM financial stress (GOI 2015), while the introduction of the national bidding trajectory in 2023 (Bridge To India 2024) reinvigorated both national - and DISCOM-led auctions. Yet, despite these supports, auction participation was restricted to a handful of DISCOMs — notably Rajasthan, Gujarat, and Maharashtra — all endowed with high solar potential and geographically proximate. Once again, regional concentration, not broad-based participation, characterised technology growth.

5.4 Chapter summary

Table 5.2 outlines the types of cost-competitiveness, when they are achieved, and the corresponding evolution of technology growth and actors' responses. There are four main takeaways from this chapter. **First**, parity emerges primarily from technology cost reductions and electricity price trends, and once achieved, in most cases, it has remained relatively static. However, parity does not directly trigger self-sustaining acceleration. Rapid growth episodes occur both

[47] *Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan Yojana* launched in 2019 by the Government of India is targeted to increase electricity supply for agricultural use, particularly to provide electricity to operate irrigation pumps.

[48] RE auctioning under the ISTS is a Government of India initiative, which began in 2018 with the goal of supplying (here, solar) electricity across state borders.

with and without parity, demonstrating that cost competitiveness alone is not the driver of solar growth in India. Once costs and prices stabilise, their role in driving further growth diminishes. Instead, long-term expansion is shaped by non-techno-economic factors. As solar grew, barriers rose. This is evident in the case of DISCOMs. Their limited institutional capacity constrained their ability to contract new solar capacity. States that initially led deployment quickly lost momentum. Financial strain forced them to scale back (e.g., Gujarat, during the first half of the acceleration phase) or withdraw from auctions altogether (e.g., Karnataka, Andhra Pradesh, Telangana, during the second half of the acceleration phase). U-parity, rather than catalysing further acceleration, exposed these institutional limits.

<table>
<tr><th>Parity type</th><th>Timing of achievement</th><th>Actors' response</th><th>Corresponding solar growth</th></tr>
<tr><td>D-parity
LCOE ≤ AT</td><td>-</td><td>Profits could not be determined, but market competition, and large developers' effort to retain market share was observed.

Discoms response not applicable.</td><td>-</td></tr>
<tr><td>U-parity
AT≤ WEP</td><td>2017</td><td>Developers keen on installing solar but key players emerge.

Discoms that previously held more auctions stop doing so, while those that held fewer auctions increase participation. National off-takers start playing a larger role.</td><td>Solar remains in acceleration phase. Yet, slow down in growth after 1 year of achieving parity.</td></tr>
<tr><td>S-parity
LCOE ≤ WEP</td><td>2021</td><td rowspan="2">Brief slow down in installations by large developers, when NTPC and Avaada led installations.

Sharp increase in the C&I segment since 2021.

Discoms in GU, MH and RA lead auctions, with those in MH and RA linked to agri-feeder scheme. Sustained high auctioning from national off-takers.</td><td rowspan="2">Solar continues to accelerate after slow-down in 2019-2022. However the year-on-year growth rate is lower than the period before slow-down.

Regional focus on capacity addition shifts from the south to the north-west. Unchanged growth in the north-east.</td></tr>
<tr><td>C-parity
PPC (solar) ≤ PPC (coal/hydro/ nuclear/wind)</td><td>2019 (S, coal)
2020 (S, wind)
2021 (India, coal)
2021 (NW, wind)
2021 (NE, coal)</td></tr>
</table>

Table 5.2: Parity type, and actual changes in actors' behaviour and technology growth.

Second, policy effort was essential to maintain momentum, and here the national government played a decisive role when barriers arose. When DISCOMs became overburdened with contracting new capacity, national-level intervention through SECI sustained momentum. Even when DISCOM-led auctions resumed, they remained concentrated in a few states (Gujarat, Maharashtra, Rajasthan), often tied to specific programs such as agricultural feeder schemes or interstate transmission, led by the national government. Similarly, when growth was disrupted by external crises, NTPC — a national government-owned utility — stepped in to keep installations moving.

Third, although market forces alone did not sustain solar growth, they decisively shaped how growth unfolded. On the developer side, the growing profitability of solar increased its attractiveness to certain developers. For example, the emergence of C-parity and S-parity created space for large industrial and commercial consumers to generate their own electricity. A shift that will require new infrastructure, demand management systems, and grid integration and reliability measures, and hence, continued policy support. Additionally, aggressive bidding and consolidation produced a small group of dominant firms with the financial capacity to set prices, withstand shocks, and expand market share. This consolidation enhanced not only their economic power but also their political position in shaping sectoral dynamics. Plus, market forces reinforced regional concentration. Solar growth remained focused in resource-rich states, but this was not explained by solar potential or market advantage alone. Policy interventions were critical in unlocking potential. For example, Gujarat benefited from a proactive state government in the early years. Rajasthan and Maharashtra expanded capacity through agriculture-focused schemes. By contrast, the north-east, despite low solar potential, remained excluded. Solar potential, therefore, amplified existing market advantages, but sustained policy engagement remained necessary for growth to materialise.

Finally, the true cost of sustaining solar acceleration and who bears it remains opaque. D-parity was not achieved during the studied period, meaning developers consistently bid below costs. This indicates persistent reliance on policy support — through subsidies, concessional finance, or other mechanisms — though the exact magnitude of support and the profit margins of developers remain unclear. What is clear is that larger developers have deliberately prioritised market share, even when profitability could not be independently verified.

6. Policy Effort and Technology co-evolution

Chapter 4 established that solar growth in India varies across states, influenced by solar potential and the institutional capacity of state distribution companies (DISCOMs). Yet, growth has followed distinct regional patterns over time. In the formative phase (until 2013), states in the north-west led capacity additions. The southern states led the early part of solar growth acceleration (between 2014–2018). From 2021 onwards, growth in the south slowed, and the north-west led acceleration again. In Chapter 5, I find that the rapid decline in the cost of producing solar electricity has led solar to achieve various types of cost competitiveness swiftly. These have influenced the capacities of solar project developers and DISCOMs to install and auction solar capacity, respectively, and their interactions with one another. Yet, cost-induced developments did not fully explain shifting growth patterns across Indian regions. Plus, some episodes of growth — temporary decline in 2019-2020 shortly after achievement of price parity in 2017 — ran contrary to market-driven explanations.

This final analytical chapter adopts the political perspective to probe into these unknowns and examine the relative role of policies in shaping solar growth in India. I explore policies based on methods in Section 3.2.3 and situate them within India's institutional and governance structures. The idea being that the organisational structure influences how policies evolve, how they diffuse within and across governance levels, and how they are eventually implemented. Additionally, I zoom out to incorporate interactions with other public and private actors involved — like national and state policymakers and other industry actors, like solar manufacturers. Ultimately, the goal is to understand how policies interact with and are shaped by technological, economic, and political changes, where changes in one cascade into and influence others, creating complex systems of mutual influence and interdependence.

To this end, this chapter is organised into four main sections. Section 6.1 lays out the institutional framework against which policy effort unfolds. Section 6.2 analyses how policy effort, in terms of policy ambition and action, evolves over time and space. Section 6.3 maps policy effort alongside technological growth and cost decline. Section 6.4 summarises the main takeaways.

6.1 Institutional framework and governance structure

Policymaking in India unfolds within a semi-federal structure, where both the national and state governments have the authority to make policies over electricity, and thus solar (GOI 2024). See Figure 6.1. In the event of a conflict between the two levels, the national counterparts take precedence. The Electricity Act of 2003 provides the legal framework for electricity generation, transmission, and distribution, guiding policy actions and the operation of the electricity market (GOI 2003).

At the national level, the Ministry of Power (MoP) oversees the overall functioning of the electricity sector, while the Ministry of New and Renewable Energy (MNRE) is specifically responsible for all RE and, hence, solar energy aspects. The Central Electricity Authority (CEA) provides expert advice on resource availability, grid connectivity, and development of long-term energy and power sector planning. These three bodies work together in setting national RE targets (IEA 2020a). MNRE oversees the Solar Energy Corporation of India (SECI), which handles the commercial implementation of solar projects, and the Indian Renewable Energy Development Agency (IREDA), which provides financial support to RE development. The Central Electricity Regulatory Commission (CERC) sets national tariff guidelines, licenses transmission, and helps define Renewable Purchase Obligations (RPOs). Initially, MNRE worked closely with CERC, CEA, and MoP to manage the off-take of solar power and minimise the government's financial burden through NTPC (National Thermal Power Corporation Limited) (Vardhan et al. 2024). From 2018 onwards, SECI stepped into this role. NTPC remains a state-owned enterprise under the MoP and is the largest power producer in India based on coal. NVVN is the financial and managerial subsidiary, which signs PPAs with project developers on behalf of NTPC. In recent years, a renewable subsidiary of the company — NTPC Green — has emerged, investing heavily into solar, nuclear, battery storage, and hydrogen. The goal of this subsidiary is to retain NTPC's market position in the sector (Pai and Jai Pai and Jai).

At the state level, governments translate national plans and strategies into on-the-ground progress by adopting policies that are tailored to specific challenges and opportunities within their respective territories (Vardhan et al. 2024). They manage electricity generation, distribution, and demand, identify project sites (e.g., solar parks), facilitate project clearances, and attract private investments (Vardhan et al. 2024). State Electricity Regulatory Commissions (SERCs), form the state-level regulatory bodies. In collaboration with the national counterpart, SERCs set local tariffs based on technology costs and market developments (IEA 2020a). They also set grid management rules and Renewable Purchase Obligations (RPOs), and issue Renewable Energy Certificates (RECs). States' fulfilment and implementation of the REC framework and compliance of RPOs is monitored by MNRE (Mannur et al. 2024; Rathore et al. 2018). Nodal agencies here provide technical and financial assistance for RE projects, helping developers navigate administrative requirements and access subsidies or incentives. SECI works with state agencies to roll out solar parks and utility-scale projects (Rustagi and Chadha 2020).

In sum, while the sector has undergone vertical unbundling — separating generation, distribution, and transmission — horizontal unbundling[49] remains minimal. When present, it remains confined to electricity generation. This has resulted in three main categories of actors within the sector with distinct capacities, interests, and relations with policymaking. See Figure 6.1.

[49]Or breaking up large monopolistic electricity companies.

First, privately owned (in purple), profit-driven entities, such as RE developers (like solar developers) or independent power producers, operate independently of policymakers. This segment is relatively small and new to the power sector, but it is emerging through recent market reforms. Private entities also include supply chain actors (e.g., solar manufacturers), who, while not directly involved in electricity generation, transmission, or distribution, play a critical role in supplying components for RE project development. Second, governments (in black) are central to solar policymaking. National entities set the overall direction, with policymakers (including politicians and technical experts) establishing industry targets, technical standards, and financial mechanisms, while incorporating input from states. Sub-national entities implement these policies, shaping market dynamics, industry developments, and actor interactions. Finally, state-owned enterprises (in green), such as power distribution and generation firms, serve as intermediaries. While they operate as businesses and engage directly with private developers and manufacturers through contractual agreements, they also remain closely tied to policymakers, often acting as implementation bodies for national and state governments.

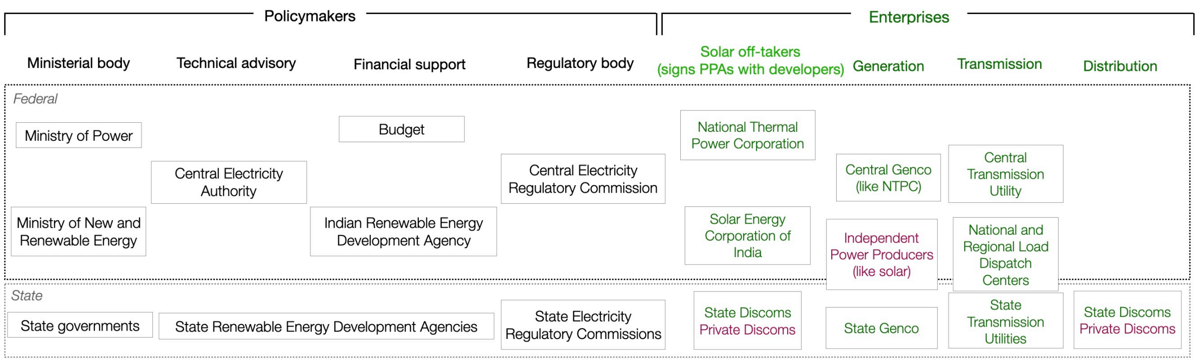

Figure 6.1: Institutional and governance framework surrounding solar electricity generation, transmission, and distribution.
The figure maps institutions and actors across national and sub-national governance levels in the Indian power sector. Policymaking bodies, including both politicians and technical experts, are shown in black; public enterprises in green; and private enterprises in purple. The figure builds on Bhowmik (2020), with additional inputs from Vardhan et al. (2024).

6.2 Changes in solar policy effort in India

Building on the institutional framework, solar policy effort evolves both at the national and state levels, but to varying degrees. Lieberman and Ross (2024) suggest that there are three ways to measure climate policy effort: through policy commitments, policy actions, and policy outcomes. Each has its own theories of change. In this chapter, I focus on the first two — policy commitments and policy actions — and examine how they change alongside policy outcomes or the growth of solar PV in India. Using methods in Section 3.2.3, I trace policy commitments by analysing the evolution of solar capacity and renewable purchase obligations (RPO) targets, and the evolution of policy actions by measuring the density and diversity of the active policy mix. The section is divided into these two parts. Throughout, I highlight the role of policymakers across national and state governance levels.

6.2.1 Evolution of policy commitments

Indian policymakers at both the national and sub-national levels have set two types of solar energy targets. Installed capacity targets, which have longer implementation timelines, and are linked to nationally determined climate pledges (MNRE 2025c). They reflect broader commitments to RE expansion and long-term infrastructure development. Renewable purchase obligation (RPO) targets, which set annual mandates primarily for electricity purchasers, such as DISCOMs and open access users. They are aimed at ensuring a steady demand for solar power in the short-term, leading up to longer-term capacity target fulfilment (Mannur et al. 2024). Both of these targets, nationally, have been ratcheted up. Yet, state and regional differences exist.

India's solar target-setting began with the Jawaharlal Nehru National Solar Mission (NSM) in 2010, which introduced targets in three phases: 1 GW by 2013, 10 GW by 2017, and 20 GW by 2022, spanning both utility-scale and rooftop solar (GOI 2010). Achieving the 20 GW would require an annual addition of roughly 1.6 GW. In 2015, recognising declining costs, improved technology, and under a new political regime, the government revised the national target to 100 GW by 2022, with 60% allocated to utility-scale projects (MNRE 2015b). This raised the required pace to about 7.6 GW annually. Following this revision, most states adjusted their 2022 targets to align with national allocations through a top-down distribution of state-specific goals. Some states, however, diverged. Maharashtra set lower targets than the national allocation[50]. Bihar retained its earlier target as it aligned with national allocation, but extended it to 2022. West Bengal did not set a solar target despite adopting a state RE policy. Nevertheless, pre-2022 targets were relatively homogeneous, typically expressed in installed capacity and differentiated by technology scale (utility vs rooftop). That said, allocation diverged across regions. Total utility scale targets accounted for 7% (18 GW) of the regional potential in the north-west, 12% (20 GW) in the south, and 15% (14 GW) in the north-east. If national allocation for Maharashtra were to be accounted for, it would have led to 15% (26 GW) also in the south. In other words, national allocation in 2022 disproportionately set higher ambitions in low-potential states. See Figure 6.2[51].

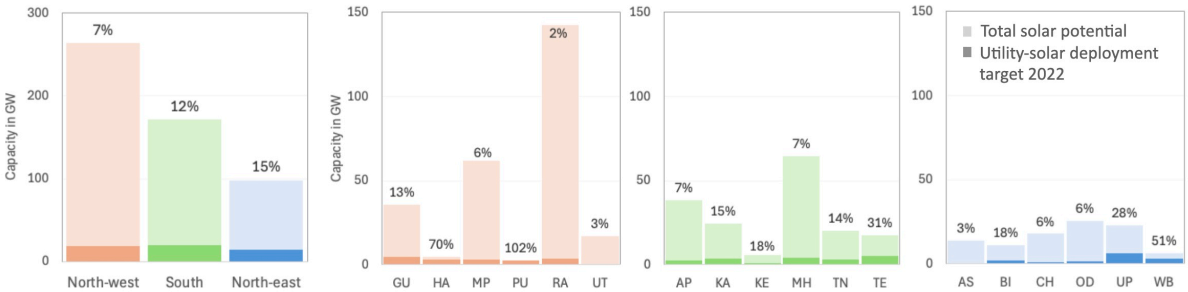

Figure 6.2: 2022 solar target allocation across states relative to their potential.
The first figure presents the national summary by regions. The subsequent figures show state-level differences within each region. Lighter areas show remaining potential, while darker areas represent fulfilled potential if 2022 targets are met. Percentages above the bars indicate the share of potential achieved under this scenario.

By 2022, Indian utility-scale solar PV achieved nearly 90% of the target. Yet, state-level out-

[50]The national government allocated 11,926 MW for Maharashtra, but the state set only 7,500 MW.

[51]Some have said the 2022 national solar energy target set in 2015 was pulled out of thin air (Shidore and Busby 2019)

comes varied (Figure 6.5). Some states — notably Karnataka, Andhra Pradesh, and Rajasthan — exceeded their targets, while others, such as Gujarat and Tamil Nadu, met theirs. In contrast, Bihar, Punjab, and Haryana grossly underperformed. Deployment and target achievement remained heavily concentrated in the north-west and the south, creating regional divergence.

At COP26 in 2021, India announced a 500 GW RE target by 2030, without specifying a solar-specific figure (McGrath 2021). Planning documents, however, project 300 GW solar by 2030, though without clear technology or state-level breakdowns (CEA 2023). This would entail average annual capacity additions of 15 GW (assuming 180 GW utility-scale solar). Beyond 2030, only the overarching 2070 net-zero goal has been set, albeit without a solar or RE-specific breakdown. Some analysts argue that 1,000 GW may be necessary by 2035 for a 1.5°C pathway (Carboncopy 2024).

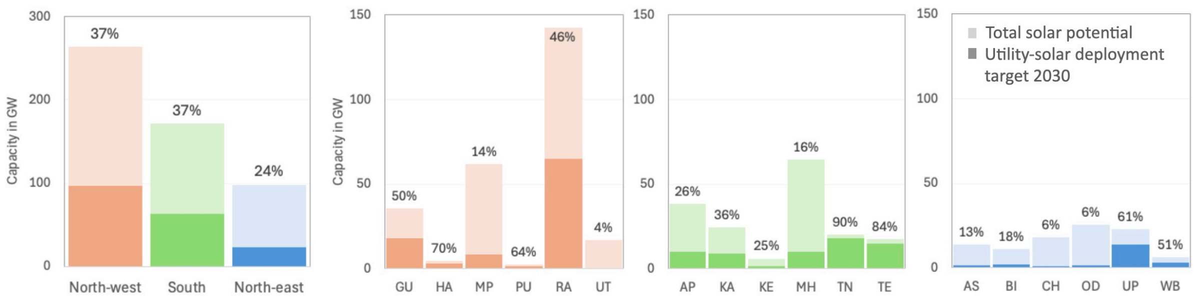

Figure 6.3: 2030 solar target distribution across states relative to their potential.
The first figure presents the national summary by regions. The subsequent figures show state-level differences within each region. Lighter areas show remaining potential, while darker areas represent fulfilled potential if 2030 targets are met. Percentages above the bars indicate the share of potential achieved under this scenario.

Post-2022 state-level targets diverge significantly, foregrounding increased state-specific motivations. Here, targets differ in timelines (e.g., some states set targets to 2030, others earlier), in focus (some set RE-wide rather than solar-specific targets), and in design (e.g., Gujarat relies primarily on RPOs rather than explicit capacity targets)[52]. National targets previously provided a strong directional signal, but states now increasingly set their own course. Ambition is concentrated in high-potential states in the south and north-west, while many eastern and north-

[52]See Methods 3.2.3 for assumptions on utility-scale solar targets.

eastern states have not adopted new targets. By 2030, utility-scale targets represent 37% of the potential in the north-west (97 GW), 37% in the south (64 GW), and 24% in the north-east (23 GW) (Figure 6.3). Unlike before, post-2022 target-setting reveals an alignment between increased ambition and states with higher resource potential. Yet reinforces ongoing regional divergence. That said, a level of national-state coordination remains implicitly visible, with targets set by states until 2030, adding up to the national goal. See Figure 6.5 and Table A.3 in the Appendix. In other words, the majority of future growth will continue to come from these 18 leading states that already dominate solar deployment.

RPO targets complement capacity targets. Both in India (Shrimali et al. 2020) and globally (Döme 2024; Smith 2020), similar policy instruments have proven central to technology adoption and cost decline. Initially, RPO targets were divided into solar and non-solar categories, but the framework has since expanded to include wind, hydro, and distributed RE, reflecting the government's push for balanced progress on RE technologies. National RPOs, set by the Ministry of Power until 2030, increase progressively, while state-level implementation is overseen by SERCs in coordination with MNRE. Significant variations within RPO frameworks persist across states: in target levels, obligated entities, compliance mechanisms, and reporting. This lack of standardisation undermines comparability (Mannur et al. 2024), hence I examine compliance based on national ambitions using methods in Chapter 3.

RPO compliance emphasises the spatial divergence. Southern states such as Andhra Pradesh, Karnataka, and Telangana, along with the northwestern state of Rajasthan, have often met their solar RPOs, while most others consistently underperform (Figure 6.4). Among some high performers in the south, growth has slowed. Karnataka, for example, has incrementally raised RPOs by just 1% without aggressively expanding solar capacity or even setting ambitious targets (Figure 6.5). The state has essentially been banking on past achievements. In contrast, Rajasthan, Andhra Pradesh, and Telangana have combined strong RPO compliance with higher capacity targets.

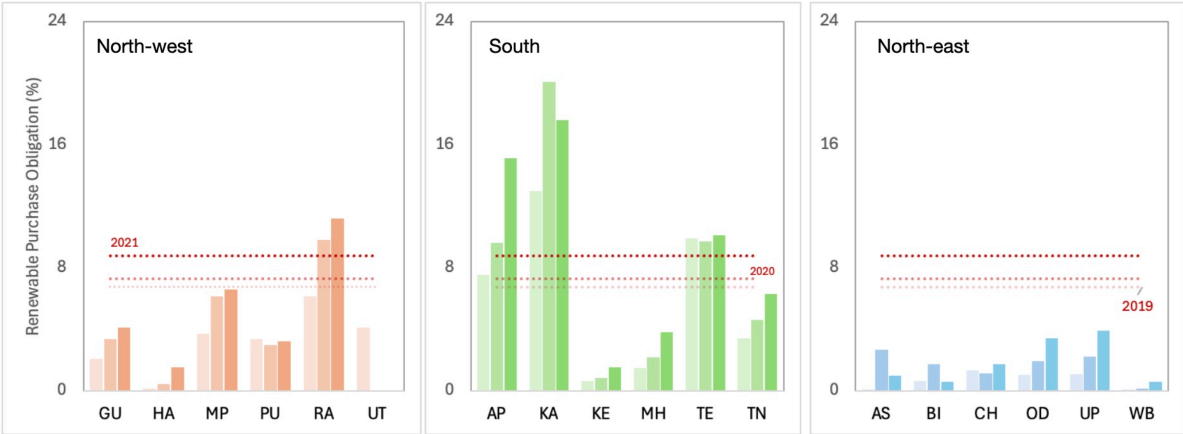

Figure 6.4: Solar RPO targets and compliance across regions between 2019 - 2021
The figure shows national solar RPO targets (dotted red lines) and state-level achievement of these targets (bars) for 2019 (light), 2020 (medium), and 2021 (dark).

At the same time, higher targets have not always translated into higher installations. Southern states such as Andhra Pradesh, Karnataka, Tamil Nadu, Telangana, and Maharashtra, along with Gujarat, Rajasthan, and Madhya Pradesh in the north-west, have generally demonstrated systematic target-setting and implementation. Yet even among these leaders, ambition has slowed in some cases — for example, Karnataka has not raised its targets — while Andhra Pradesh and Telangana have witnessed slower deployment. In most other states, targets remain inconsistent: frequently raised or lowered without matching deployment trends, or not set at all (e.g., Bihar, Odisha, West Bengal, Chhattisgarh). This reflects a fundamental divide between systematic and erratic target-setters.

Figure 6.5 provides an overview of the evolution of solar capacity targets at both the national and state levels. Essentially, three main groups of states emerge: states where targets are raised and achieved, concentrated in the south and north-west; States where targets are raised but rarely achieved, including Kerala and Maharashtra in the south, Assam and Uttar Pradesh in the north-east, and Uttarakhand in the north-west; and States where targets are not raised and not met, primarily in the north-east, as well as Punjab and Haryana in the north-west. Karnataka represents an anomaly: targets have been achieved in the past, yet have not been raised further.

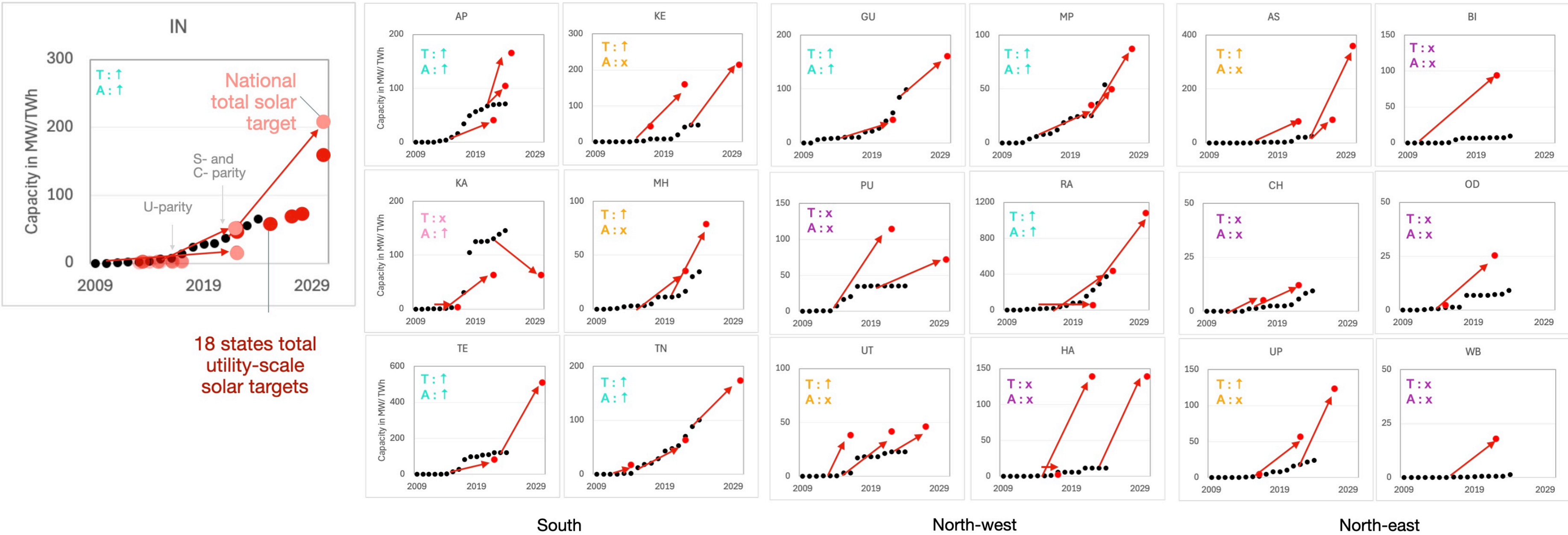

Figure 6.5: Change in solar capacity targets in India and across states.

Red dots indicate utility-scale solar targets, and red arrows show when these targets were set. Black dots represent actual capacity deployment. All capacity values are normalised to total electricity generation in 2015. States are grouped by region: from left to right, the first two columns are southern states, followed by northwestern, and then northeastern states. Coloured labels within the graphs indicate (i) whether targets (T) were raised (↑) or not (x), and (ii) whether targets were achieved (A) in the past (↑) or not (x). This categorises states into four groups: targets achieved and raised (blue labels), targets achieved but not raised (pink labels), targets not achieved but raised (yellow labels), and targets neither achieved nor raised (purple labels). The majority of the blue and yellow labelled states are in the south and the north-west high potential regions.

In sum, India's solar policy commitments have evolved through a nationally coordinated but regionally uneven process. Initially, targets were solar-specific and centrally driven. Since 2022, they have broadened to RE-wide frameworks with greater state-level variation. While ambitious targets have often spurred growth, they have not guaranteed it, and many states continue to underperform. Policy ambition and deployment remain concentrated in the south and north-west, reinforcing divergence rather than convergence in India's solar landscape.

6.2.2 Evolution of policy actions

Figure 6.6 shows that despite cost decline and increase in competitiveness, the density of the active policy mix has continuously increased. In other words, policies removing barriers surrounding solar PV in India did not decrease even after costs declined. Rather, more policies were adopted to maintain acceleration. The observation stands both at the national and state levels, with the former typically outnumbering the latter. See Figures 6.6 and 6.7. The approach to policy-making differed between the two government levels. The push for policy action came from the national government, focusing on broader goals like energy security, political ambitions, and economic development. At the state level, policymaking translated national goals into localised actions, considering resources, technology, and infrastructure (Rathore et al. 2018).

However, policy diffusion did not always develop linearly — national policies responded to regional needs and drew on lessons from regional experiments, where policies were first piloted in different states before being nationally adopted. For example, the agriculture-focused solar scheme was introduced in 2018 in Gujarat and Maharashtra before the national *Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan Yojana* (or KUSUM) scheme was launched in 2019. Once such policies were adopted at the national level, states followed suit. As a result, over time, states have adopted similar types of policies with variations in policy design (Shrimali et al. 2020). Consequently, I find no significant relationship between the total density of the active policy mix and spatial differences in solar growth among states.

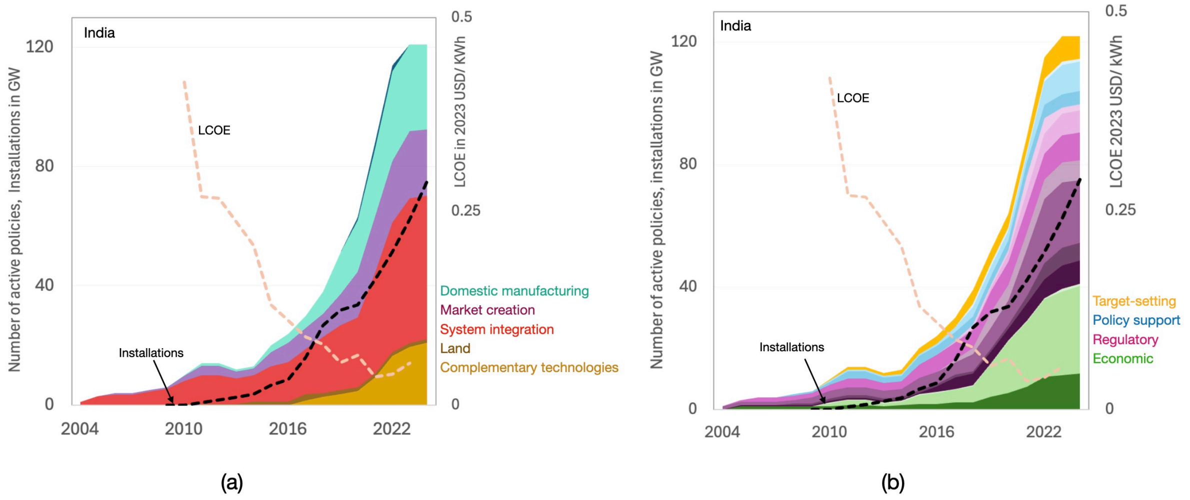

Figure 6.6: Change in policy priorities (panel a) and policy instruments (panel b) within the national active policy mix.
State-specific findings are in Figures A.10 and A.11 in the Appendix.

Alongside increasing policy density, the diversity of policies has also grown both in terms of priorities and instruments. See Figures 6.6 and 6.7. In other words, as solar expanded and markets matured, new and diverse challenges emerged, requiring targeted policy responses. These responses have stemmed from socio-technical developments (e.g., policies for system integration, such as curtailment protection through must-run regulations and support for complementary technologies like storage and hybrids to address solar variability), or from policy learning (e.g., policies around guaranteeing payment security to solar developers in the face of failing DISCOMs), or a combination of the two (e.g., agriculture-focused solar installation scheme was started to find synergies and mitigate multiple barriers like land availability, backlash from farmers, aiding failing DISCOMs, and ensuring electricity supply for agriculture use). Interestingly, old priorities did not simply disappear during the studied period. New ones were continually layered on top of existing ones, which may be a result of a new market that is still emerging or point to bureaucratic malfunctioning (Fernández-i-Marín et al. 2024) or policy dependencies that make existing policies difficult to dismantle (Laird 2016).

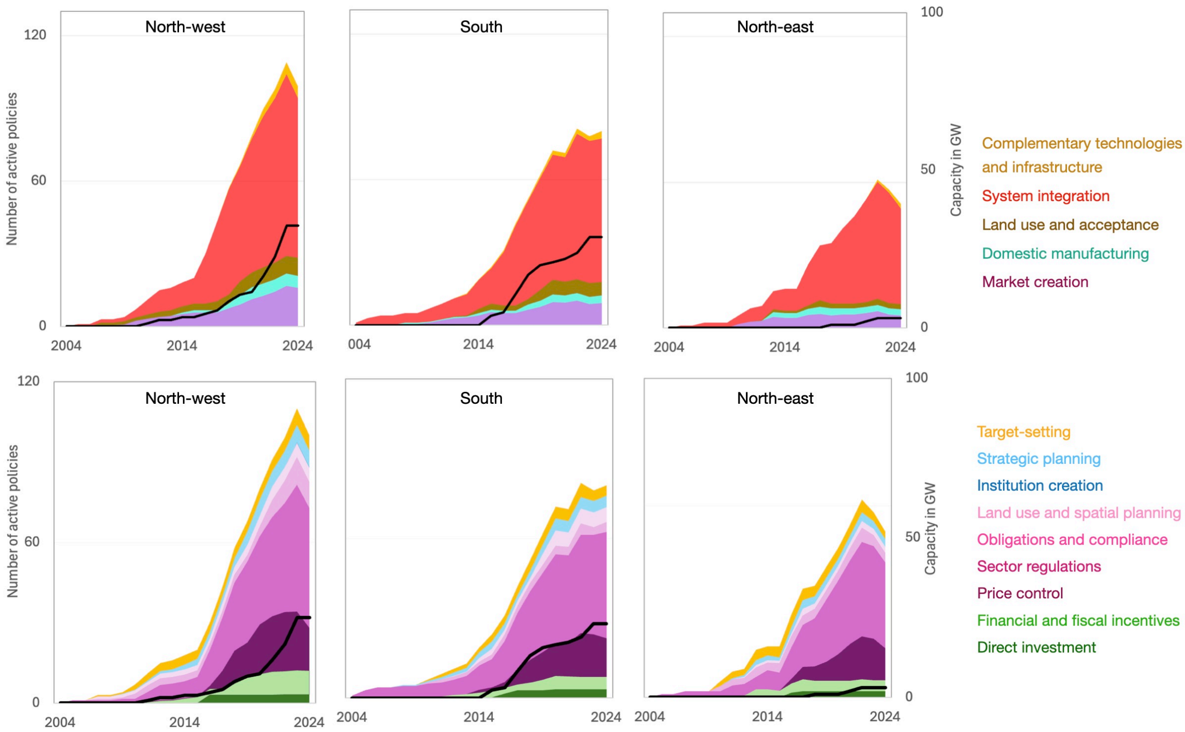

Figure 6.7: Change in policy priorities (top row) and policy instruments (bottom row) within the state active policy mix, grouped by regions.
See Figures A.10 and A.11 in the Appendix for state-specific results.

The evolution of policy instruments at the highest level is relatively stable nationally and sub-nationally, essentially focused on regulatory and economic instruments. See Table 6.2. In contrast, the evolution of policy priorities is dynamic, particularly at the national level, reflecting that not only multiple priorities were pursued simultaneously, but also that some gained prominence during specific periods of time. See Table 6.1. For example, there has been a growing focus on complementary technologies policies in recent years, while the emphasis on land policies initially rose but gradually declined. Throughout, system integration policies remained dominant nationally and sub-nationally, highlighting a regulated electricity market context with ongoing market reform efforts. The point of interest here is that Indian policy-makers not only had to promote solar uptake but also had to enable the establishment of an electricity market framework, ground up.

		Market creation	Domestic manufacturing	System integration	Complementary technologies	Land use and acceptance	Total active policies	Installations (MW)
India (National)	2004 - 2009	8 %	0 %	92 %	0 %	0 %	6	10
	2010 - 2013	19 %	6 %	73 %	0 %	2 %	12	2631
	2014 - 2018	21 %	19 %	50 %	7 %	3 %	38	26763
	2019 - 2020	24 %	28 %	37 %	8 %	2 %	63	33598
	2021 - 2024	18 %	24 %	40 %	17 %	1 %	121	75190
North-west	2004 - 2009	21 %	0 %	46 %	0 %	33 %	4	2
	2010 - 2013	27 %	0 %	58 %	0 %	15 %	16	557
	2014 - 2018	13 %	4 %	76 %	1 %	6 %	57	3179
	2019 - 2020	14 %	6 %	70 %	2 %	8 %	79	4207
	2021 - 2024	16 %	5 %	67 %	5 %	7 %	99	11967
South	2004 - 2009	10 %	10 %	80 %	0 %	0 %	5	6
	2010 - 2013	24 %	4 %	67 %	3 %	3 %	13	362
	2014 - 2018	12 %	4 %	78 %	2 %	4 %	52	7693
	2019 - 2020	13 %	4 %	72 %	2 %	8 %	72	8630
	2021 - 2024	11 %	4 %	74 %	4 %	7 %	80	10933
North-east	2004 - 2009	0 %	0 %	100 %	0 %	0 %	2	2
	2010 - 2013	30 %	13 %	50 %	0 %	7 %	15	31
	2014 - 2018	14 %	9 %	71 %	0 %	6 %	35	793
	2019 - 2020	12 %	5 %	78 %	0 %	4 %	46	1102
	2021 - 2024	10 %	5 %	77 %	4 %	4 %	51	1750

Table 6.1: Change in policy priorities nationally and across regions over key time periods.

		Direct investment	Fiscal incentives	Market based	Price control	Trade policy	Sector regulations	Production standards	Obligation & compliance	Spatial planning	Guidelines	Extensions	Information	Institution creation	Strategic planning	Target-setting
India (National)	2004 - 2009	17 %	0 %	0 %	8 %	8 %	33 %	0 %	25 %		0 %	0 %	0 %	8 %	0 %	0 %
	2010 - 2013	8 %	8 %	3 %	4 %	7 %	21 %	0 %	21 %		0 %	0 %	0 %	15 %	4 %	8 %
	2014 - 2018	6 %	13 %	1 %	10 %	2 %	14 %	5 %	16 %		1 %	3 %	3 %	7 %	8 %	12 %
	2019 - 2020	8 %	26 %	1 %	6 %	2 %	13 %	8 %	12 %		4 %	2 %	2 %	5 %	5 %	7 %
	2021 - 2024	10 %	23 %	1 %	6 %	5 %	17 %	5 %	7 %		6 %	2 %	1 %	4 %	8 %	6 %
North-west	2004 - 2009	0 %	5 %		5 %		30 %		13 %	30 %					5 %	13 %
	2010 - 2013	0 %	7 %		1 %		38 %		16 %	11 %					7 %	21 %
	2014 - 2018	5 %	7 %		21 %		44 %		5 %	5 %					5 %	7 %
	2019 - 2020	4 %	10 %		23 %		41 %		5 %	5 %					8 %	5 %
	2021 - 2024	3 %	9 %		16 %		45 %		10 %	5 %					6 %	6 %
South	2004 - 2009	0 %	10 %		0 %		80 %		0 %	0 %					10 %	0 %
	2010 - 2013	2 %	9 %		0 %		53 %		11 %	2 %					11 %	12 %
	2014 - 2018	6 %	6 %		16 %		50 %		6 %	4 %					5 %	8 %
	2019 - 2020	5 %	7 %		17 %		47 %		4 %	8 %					6 %	6 %
	2021 - 2024	4 %	6 %		18 %		50 %		5 %	7 %					5 %	5 %
North-east	2004 - 2009	0 %	0 %		0 %		100 %		0 %	0 %					0 %	0 %
	2010 - 2013	0 %	17 %		0 %		27 %		20 %	4 %					10 %	23 %
	2014 - 2018	6 %	9 %		13 %		43 %		9 %	5 %					6 %	10 %
	2019 - 2020	4 %	7 %		18 %		49 %		6 %	4 %					5 %	7 %
	2021 - 2024	4 %	7 %		19 %		52 %		6 %	4 %					5 %	5 %

Table 6.2: Change in policy instruments nationally and across regions over key time periods.
Colours indicate instrument clusters: green for economic instruments, red for regulatory instruments, blue for policy support instruments, and yellow for target-setting instruments.

In terms of policy instruments, early-year policies focused on foundational support, such as institution creation and target setting. As the policy framework matured, regulatory and economic instruments grew in prominence — aimed at optimising operations and addressing emerging challenges. In other words, the evolution of policy priorities and instruments has its own temporal dynamics. Notably, as solar grew, economic instruments (or those that require public spending) did not go away. Rather, their share was maintained sub-nationally and grew nationally, suggesting a persistent need for government spending. That said, the specific magnitude of this financial support remains unknown, both in total and specifically to different priorities over time. For example, spending towards different priorities may shift over time. In India, financial support shifted from subsidising the cost of solar electricity at early stages of growth to public spending on developing storage and grid expansion.

Plus, a specific mix of instruments was used to address different policy priorities, and this configuration also varied across governance levels. While there can be a temporal dimension to this relation, I capture a snapshot of this relationship from the active policy mix as of 2024. Three main observations stand out. See Figure 6.8. First, each policy priority is addressed through a distinct set of instruments. Market creation policies rely on a balanced mix of instruments, including subsidies and auctions (economic), renewable purchase obligations (regulatory), and long-term planning (policy support and target-setting). In contrast, domestic manufacturing relies more on economic instruments (e.g., import duties, R&D support), and system integration has relied more on regulatory measures (e.g., power sector reforms). Second, the mix of instruments used for each priority differs between the national and state levels. In other words, policymakers at both levels address the same priority using a different mix of instruments. For example, in land acquisition, the national government sets targets and provides financial assistance to states for developing solar parks. In contrast, states make regulations on land use and spatial planning, as land falls under state jurisdiction in India (GOI 2024). Another example is that national complementary technology policies rely more on economic and policy support instruments. States, on the other hand, primarily use regulatory measures (e.g., balancing measures, grid integration, and open access). This reflects how national policymakers set the broader policy framework, while states manage the implementation of this framework at the sub-national level, especially regarding aspects concerning the operation of a non-liberalised electricity market.

Finally, the national policy mix reveals greater diversity of instruments, particularly with more space for economic measures, and priorities are more dynamic overall. In contrast, state policies are mostly directed at regulatory instruments targeting system integration. See also Table 6.2. In other words, policies at different governance levels varied not only in their attitude but also in their areas of responsibility. National counterparts had greater financial capacity overall, while states have more regulatory capacity to facilitate system integration and land accessibility. This finding is also supported by the density of specific policy types showing a modest (positive) relation with differences in solar growth across states. For example, while the total number of active policies did not have any significant relationship with spatial differences in growth, I find a moderate positive relationship ($R^2 = 0.51$) between the number of land-use and system integration policies and differences in technology adoption across states. However, the direction of causality remained unclear. It could be that more of these policies drive higher solar growth, or that greater adoption creates the need for more such policies.

Figure 6.8: The policy instrument mix used to address different priorities at the national (panel a) and state (panel b) levels.

6.3 Technology-cost-policy co-evolution in India's solar sector

Socio-technical barriers — such as grid integration, market creation, and land availability — arise at different points in time and vary across space, shaping when and how policies responded to solar growth in India. Yet, these barriers alone do not explain India's solar trajectory. I show that the evolution of solar policy efforts in India cannot be understood as a simple response to socio-technical developments. Rather, it reflects a dynamic interplay between cost decline, technology growth, policy changes, and regional contexts. Essentially, this co-evolution can be mapped across five distinct time periods: the early years of foundational policymaking (2004–2009) between the Electricity Act of 2003 and the first national solar policy; the late formative phase (2010–2013) when policies were introduced but growth remained modest and concentrated in the north-west; the first half of the acceleration phase (2014–2018), marked by rapid expansion in southern states; the slowdown (2019–2020), when growth plateaued nationwide; and the second half of the acceleration phase (2021–2024), when momentum re-shifted back to north-western states. Comparing these phases highlights why solar growth has remained regionally concentrated and temporally uneven, and shows that national policy effort has been the most consistent driver of India's solar trajectory. Table 6.3 summarises the key developments for each phase for India as a whole.

6.3.1 2004 – 2009: The era of foundational policymaking

This period marked a transition between major electricity market reforms and the introduction of the first national solar policy. It established the context in which India's utility-scale solar and policy efforts surrounding it took shape. Like most mature RE sectors globally today, solar first entered the Indian energy landscape after the 1970s oil crisis (Vardhan et al. 2024). Early adoption concentrated on decentralised systems for rural and remote electrification (Vardhan et al. 2024). For decades, policy support and deployment stagnated. The power sector was vertically integrated and dominated by public ownership. The economic liberalisation of the 1990s triggered sweeping sector reforms, culminating in the 2003 Electricity Act (GOI 2003). The Act explicitly sought to expand private participation in power generation and accelerate RE adoption, reflecting global trends. The 1990s also brought sharpened attention to climate change (Zillman 2009). Building on this momentum, India adopted the National Action Plan on Climate Change in 2008 under the UNFCCC framework, aligning with the principle of common-but-differentiated responsibilities (GOI 2008). The National Solar Mission emerged directly from this plan.

Between 2004 and 2009, the policy mix remained thin but pivotal. Policymaking prioritised liberalisation while laying the foundations for large-scale RE expansion. Key measures included the introduction of the RPO framework, open access, and direct financial support to state DISCOMs for costly RE procurement. Developers were incentivised with generous feed-in tariffs (FiTs) that signalled strong policy commitment. Solar deployment remained minimal nationwide, as the technology was still in its formative phase. However, Gujarat in the north-west broke new ground by launching India's first solar policy in 2009, preceding national adoption. With strong state backing under then-leader Narendra Modi, state DISCOMs signed 1 GW of solar PPAs at tariffs as high as 0.24 USD/kWh (2023 standards), later declining to 0.08 USD/kWh in the second half of the project lifetime (Shidore and Busby 2019). Others, like the neighbouring state of Rajasthan, chose caution, holding back until national policy was in place (Sareen 2018).

	Socio-technical developments		Techno-economic developments		Political developments and external events		National policy developments			Spatial focus
	Growth	**Emerging barriers**	**Costs and tariffs**	**Parity events**	**Politics**	**External events**	**Solar targets**	**Policy density**	**Types of new policies**	**Regions & state leaders**
2004 - 2009	0 GW, Formative, Take-off in 0 states.	High technology costs.	-	-	Rise of a political entrepreneur in GU.	Power sector re-structuring. Global climate action gaining momentum	-	6	New policies established frameworks for RE integration and large-scale private sector participation. FiT based compensation for solar.	-
2010 - 2013	3 GW, Formative, Take-off in 4 states.	High technology costs, grid integration.	Rapid decline in costs and tariffs.	-	Political entrepreneur campaigns for national leadership.	-	22 GW by 2022	12	National solar policy adoption. New policies are layered into existing frameworks, supporting rather than disrupting current regimes. Start of auction-based compensation.	North-west (GU)
2014 - 2018	27 GW, Accelerating, Take-off in 13 states.	Land acquisition, grid integration, lack of payment security from discoms, discontent among domestic manufacturers.	Rapid decline in costs and tariffs.	U-parity in 2017.	National regime shift towards the political entrepreneur. Successful consolidation of manufacturers' interests.	WTO rules against India on LCR in solar auctions.	100 GW by 2022 (60 GW from utility-scale)	38	New policies protect key actors' interests while creating synergies with complementary technologies.	South (AP, KA, TE)
2019 - 2020	34 GW, Slowdown, Take-off in 14 states.	Same as earlier except discontent among domestic manufacturers wane. Increase in cost of production.	Cost decline slows and tariffs stabilise.	C-parity in south in 2019.	Stable national leadership.	Global pandemic	-	63	New policy mix follow established paths but reveal contradictory tensions. Policies also included crisis response.	North-west (GU, RA)
2021 - 2024	75 GW, Accelerating, Take-off in 15 states.	Same as earlier.	Tariffs largely stable. Costs rise.	S-parity & C-parity in 2021	Stable national leadership.	Supply chain disruptions Anticipation of EU's CBAM	300 GW by 2030 (assuming 180 GW from utility-scale)	121	New policies boost support for complementary technologies and infrastructures, and system integration. First policy to phase down coal.	North-west (GU, RA)

Table 6.3: Technology-cost-policy co-evolution in India's solar sector

6.3.2 2010 – 2013: Late formative years of solar deployment

This period marked the formal launch of India's solar era with the adoption of the first national-level solar policy. The technology was still nascent and at the formative phase of growth. The Jawaharlal Nehru National Solar Mission (JNNSM or NSM), adopted in 2010, set an ambitious target of 20 GW of grid-connected solar capacity by 2022 (GOI 2010). This immediately triggered a wave of state-level solar policies, as states aligned themselves with national ambitions. Policy density and diversity expanded rapidly but soon stabilised, reflecting a cautious wait-and-see approach. See Figure 6.6. Rather than creating entirely new frameworks, policy-makers layered new measures onto existing structures from the previous phase, opening space for both established and emerging players. For example, NTPC, India's dominant thermal generator, began bundling coal with solar generation. (See Figures 5.8 and 5.7, developers with 5% market share.) Developers received generous incentives — subsidies, tax benefits, and cost waivers — that strongly favoured project deployment (also in Rustagi and Chadha (2020)). In contrast, solar component manufacturers were primarily supported through local content requirements (LCRs) (Behuria 2020).

At the same time, fiscal measures such as competitive auctions redefined the market. Developers bid for projects, with the lowest tariff applied for the project's lifetime, introducing price discovery and efficiency discipline into the sector. Regulatory protections were also codified early. Solar plants received must-run status, ensuring that technical curtailment for grid stability did not translate into financial losses, and interstate transmission fees for solar electricity were waived (also in Rao and Agarwal (2021)). Although such protections usually appear in advanced stages of technology diffusion (**?**), India introduced them early due to grid constraints, almost in parallel with its first solar policy.

Global technology learning combined with domestic policy rapidly drove down costs and tariffs (see Figure 5.2, LCOE and AT evolution). Installations scaled quickly but unevenly across states, with only four out of 18 registering take-off (see Figure 4.3). The north-west, particularly Gujarat and Rajasthan, emerged as frontrunners. Politically, Gujarat's success in solar energy elevated Narendra Modi's reputation as a decisive and proactive administrator. He leveraged this record in his national election campaign, positioning himself as a champion of solar energy and presenting a vision of India as a global solar power leader (Shidore and Busby 2019). By the end of this phase, Modi assumed the national office, ushering in a new political regime and a coalition strongly aligned with solar expansion. In 2014, solar had reached national take-off, contributing 0.5% of the electricity supply, ushering a decade-long period of sustained acceleration in the country.

6.3.3 2014 – 2018: First acceleration phase of solar growth

This phase extended the rapid decline in solar costs and tariffs from the previous period (see Figure 5.2, LCOE and AT evolution). More states scaled up solar adoption, driven by favourable economics and strengthened policy mandates. By now, 13 of 18 states had achieved take-off (Figure 4.3). Solar growth shifted to an exponential trajectory. Southern DISCOMs, along with national government interventions, particularly in Karnataka, Andhra Pradesh, and Telangana, drove installations through aggressive auctioning, creating a peak in deployment concentrated in these three states (Figure 4.1). Innovation and competition pushed tariffs down sharply. By 2017, price-parity (U-parity) was achieved (Figure 5.4), allowing DISCOMs to sign solar contracts at rates comparable to conventional electricity. This milestone signalled solar's transition from a niche option to a mainstream power source. Some argue that such milestones unleash self-sustaining growth where market forces dominate (Nijsse et al. 2023). In India, however, systemic vulnerabilities surfaced, requiring continuous policy intervention to sustain momentum. Policies were increasingly focused on removing barriers for three main actor groups. Figure 6.9 shows annual national-level policy adoption alongside capacity additions.

First, developers. Policies streamlined land acquisition through the 2014 Solar Parks and Ultra

Mega Projects scheme; managed balancing-related deviations with the 2015 Deviation Settlement Mechanism; and extended the validity of un-purchased Renewable Energy Certificates. In 2017, the MNRE introduced competitive bidding guidelines to standardise auctions and improve transparency. From 2018, central entities such as SECI assumed leadership in auctions, reducing developers' exposure to financially weak DISCOMs and expanding pan-India auctions under the Inter-State Transmission Scheme (ISTS) framework (Rustagi and Chadha 2020). To address grid bottlenecks, the national government launched the Green Energy Corridor scheme in 2015, building transmission capacity dedicated to RE[53]. Meanwhile, policies targeted new constituencies, particularly those with conflicting interests. The KUSUM scheme incentivised farmers to adopt solar pumps, generate their own electricity, and sell excess power to DISCOMs (MNRE 2025b). Similarly, the 2018 Solar-Wind Hybrid Policy promoted hybridisation of solar and wind projects to increase reliability and round-the-clock supply.

Second, DISCOMs. Their financial weakness emerged as a binding constraint on solar growth. Gujarat illustrates this. After signing 1 GW of contracts around 2009, its DISCOMs avoided new auctions for eight years, burdened by high-tariff PPAs (see Figures 4.1 and 5.9). In the south, DISCOMs leading growth struggled with debt and operational inefficiencies. As tariffs fell, DISCOMs in Andhra Pradesh and Tamil Nadu attempted to renegotiate existing contracts (Prateek 2019b), creating revenue uncertainties for developers. Gujarat even cancelled finalised tenders (Prateek 2019a). To address these risks, the government launched the Ujwal DISCOM Assurance Yojana (UDAY) in 2015, transferring 75% of DISCOM debt to state governments (GOI 2015). The goal was to improve the sector's financial health, encourage RE adoption, and ensure a reliable electricity supply. Complementary measures, such as the agri-feeder (KUSUM) scheme, provided central financial support for DISCOMs to purchase solarised farmers' surplus power, effectively institutionalising agricultural cross-subsidies further (MNRE 2025b).

[53]The Green Energy Corridor Policy was conceptually developed from a September 2012 study by the Power Grid Corporation of India Limited, highlighting the need for dedicated transmission infrastructure for RE.

Third, domestic manufacturers. They faced relentless competition from subsidised Chinese imports (Clover 2017). Early protections, such as LCR requirements in auctions, proved inadequate as developers favoured cheaper imports (Clover 2017; Sullivan 2017). Plus, in 2015, the US challenged India at the World Trade Organization (WTO), which ruled in 2016 against India's LCR policy (Reuters 2015). India responded with the Central and State Public Sector Undertakings scheme (2015), under which projects auctioned would be required to use only Indian-made cells and panels, but the power generated could only be used by government-owned companies (Rustagi and Chadha 2020). However, its impact remained limited. The turning point came in 2018, when India imposed safeguard duties on imported solar cells and modules to shield the domestic industry (MNRE 2018), mirroring similar measures in the US (Lawder and Groom 2018), though unlike the EU, which refrained from such protectionism (Enkhardt 2024).

Policy trajectories were also shaped by political shifts. On taking office in 2014, Narendra Modi quintupled the 2022 solar target to 100 GW (MNRE 2015b) and launched the International Solar Alliance (ISA) in 2015, the first international organisation headquartered in India. This central push expanded policy adoption across national and state levels (Figures 6.6 and 6.7), backed by sharply higher central funding allocations. See Figure A.2 in the Appendix. Modi also acted as an agent of policy diffusion, scaling successful Gujarat models nationally. For instance, Charanka Solar Park became the basis of the national solar park policy in 2014, with revised upward targets in 2017. The push for domestic manufacturing also reflected regime change. Between 2010–2015, multiple industry appeals for protection went unanswered (Behuria 2020). By 2017, however, Adani's Mundra Solar, with the largest developer market share (Figure 5.7) and major manufacturing investments, led a coalition lobbying for trade protection (Behuria 2020). Despite resistance from developers and a temporary Tamil Nadu High Court stay, the Supreme Court reinstated safeguard duties in 2018 (Kenning 2018). This episode marked a political and industrial turning point, driven by (i) technology growth and market

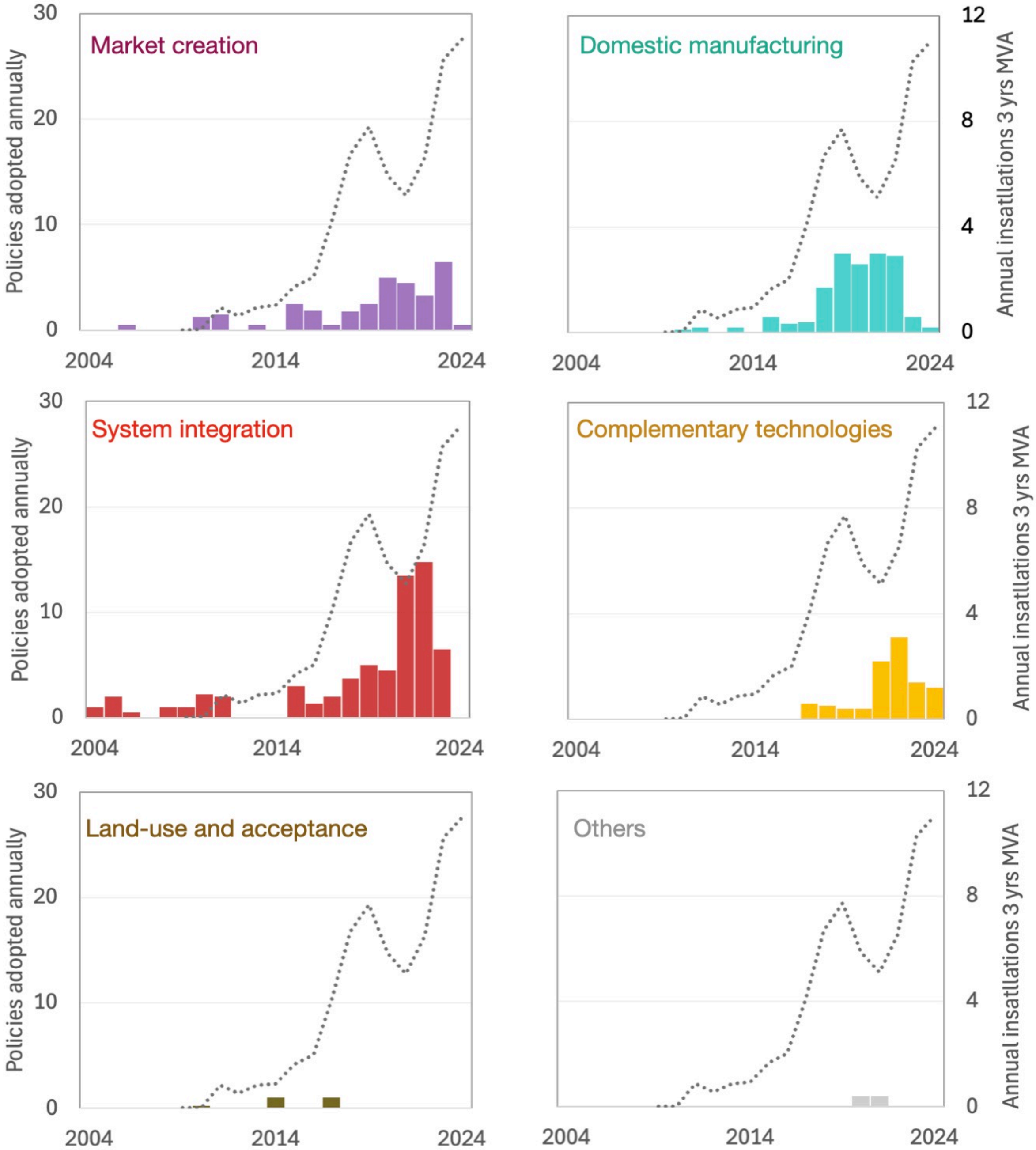

Figure 6.9: Change in annual adoption of national policies, grouped by priorities.
The primary y-axis shows active policy density, while the secondary y-axis shows three-year moving average of annual capacity additions (dotted line) in GW.

consolidation, (ii) stronger industry lobbying, and (iii) Modi's alignment with business groups and emphasis on energy sovereignty.

6.3.4 2019 – 2020: Temporary slowdown in solar growth

Despite favourable techno-economic conditions (solar had already achieved U-parity in 2017), this period was defined by a temporary slowdown in growth. In other words, even with better economics and stronger policy effort, deployment stalled — nationally and sub-nationally, with the most pronounced slowdown in the southern region (Figure 4.1). While northwestern states maintained steady installation levels in 2019, southern leaders such as Karnataka, Andhra Pradesh, and Telangana saw capacity additions collapse, with no subsequent recovery (Figure 4.2). Yet, one more state - Haryana in the north-west - reached take-off (Figure 4.3). The policy mix, already dense and diverse in the previous phase, expanded further (Table 6.1). As adoption grew, new barriers emerged, prompting policies to balance competing priorities and actor interests. A notable shift occurred toward supporting domestic manufacturing, signalling its rising political salience (Figure 6.9). However, this shift disrupted the previous equilibrium that favoured developers. The turning point was the 2018 import duty on solar cells and modules. Developers anticipated the duty, which could have spurred pre-duty installations, but its imposition immediately depressed new commissioning across developers (Figure 5.8).

The new policy mix favoured domestic manufacturers and solar developers, but the short-term interests of these two profit-driven private actors were not aligned. While designed to protect manufacturers, these measures exposed developers to rising input costs without compensatory relief. Although LCOE continued to decline, import duties eroded these gains, leading to tariff stabilisation from 2018 onward (Figure 5.2). This created conflicting incentives between manufacturers and developers. Until then, most solar projects relied on cheap, efficient imports, while domestic manufacturing remained weak and delayed (Behuria 2020). By 2018, overlap between the two sectors was minimal; only Adani had invested in both development and manufacturing. With the sector dependent on low-cost imports, import duties upended the incentive structure that had enabled developer-led growth (Behuria 2020). Developers warned that the duties "compromised" India's solar ambitions and risked being counterproductive (Chandrashekan 2018). Auction tariff caps further constrained developers, preventing cost pass-through and squeezing profit margins (Chandrashekan 2018).

Annual capacity additions began to fall in 2019, a decline compounded in 2020 by COVID-19 lockdown-related commissioning delays (Figure 6.10). This was further magnified due to supply disruptions from the polysilicon shortage that ran until mid-2022 (IRENA 2024a). As a result, from 2018 onward, the sector faced persistent under-subscription in solar auctions, which continued until 2022 (Figure 5.10). This episode highlighted a paradox: policy can catalyse rapid growth, but when shaped by consolidated interest groups, it can also unintentionally stall momentum — a dynamic that external shocks, such as the pandemic, further amplify. A second relevance of this episode is that it challenges simplistic notions of technology leapfrogging in technology-recipient countries. Policymakers in such contexts face a trade-off: accelerated renewable energy (RE) growth versus domestic industrial development. Pursuing the former would entail rapid technology transfer and potential leapfrogging, while the latter requires navigating a long, R&D-driven formative phase and accepting slower growth. The Indian experience demonstrates that even when policymakers choose the former accelerated path, industrial pressures still emerged and bore negative consequences on growth, which also required additional policy support. This occurs because the RE sector is predominantly private, with actors motivated by profit rather than climate mitigation, meaning industrial dynamics shaped outcomes independently of initial policy choices.

6.3.5 2021 – 2024: Acceleration of growth post slowdown

The slowdown was brief and did not derail the long-term trajectory of solar growth in India. This is contrary to what many had predicted Chandrashekan (2018). During this period, take-off was now achieved in 15 of 18 states. This phase shifted the regional focus, led by Rajasthan and Gujarat, in the north-west. The region added nearly three times the capacity of southern states, where growth had slowed significantly. Despite the slowdown, nationwide techno-economic progress continued, with S-parity and C-parity achieved by 2021 (Figures 5.4 and 5.6). This raises a critical question: how did solar rebound so quickly despite import taxes, ongoing pandemic disruptions, and persistent under-subscription of auctions up to 2022? I find that the recovery was driven by mutually reinforcing dynamics across policy effort and cost decline.

Much like the previous phase, the active policy mix expanded, with a stronger focus on system integration and support for complementary technologies, timed closely with the 2021 acceleration. Evidence suggests that both the avoidance of prolonged slowdown and the need for these policies were shaped by policy decisions made in 2017. Following the adoption of national auction guidelines, 2018 onwards central entities such as SECI and NTPC began conducting auctions in addition to those managed by state DISCOMs (Figure 5.9 and 6.10). This had three effects. First, import taxes raised production costs for developers, but reliable off-takers beyond financially unstable state DISCOMs mitigated investment risks. Second, many national auctions were pan-India under the ISTS scheme, allowing developers to choose installation sites based on profitability. This led developers to concentrate capacity in high-potential north-western states of Gujarat and Rajasthan, making these the primary growth drivers. These installations also aligned with the national government's broader goal of diversifying electricity generation across regions and building new grid infrastructure.

Third, the achievement of cost parity (S-parity) and cross-source parity with coal (C-parity) followed a growth among commercial and industrial (C&I) consumers. This segment increased pressure on infrastructure and system integration, reinforcing the need for policies targeting system integration, complementary technologies, and infrastructure development (See Figures 5.8 and 6.9). DISCOMs in states that persisted in conducting successful auctions included

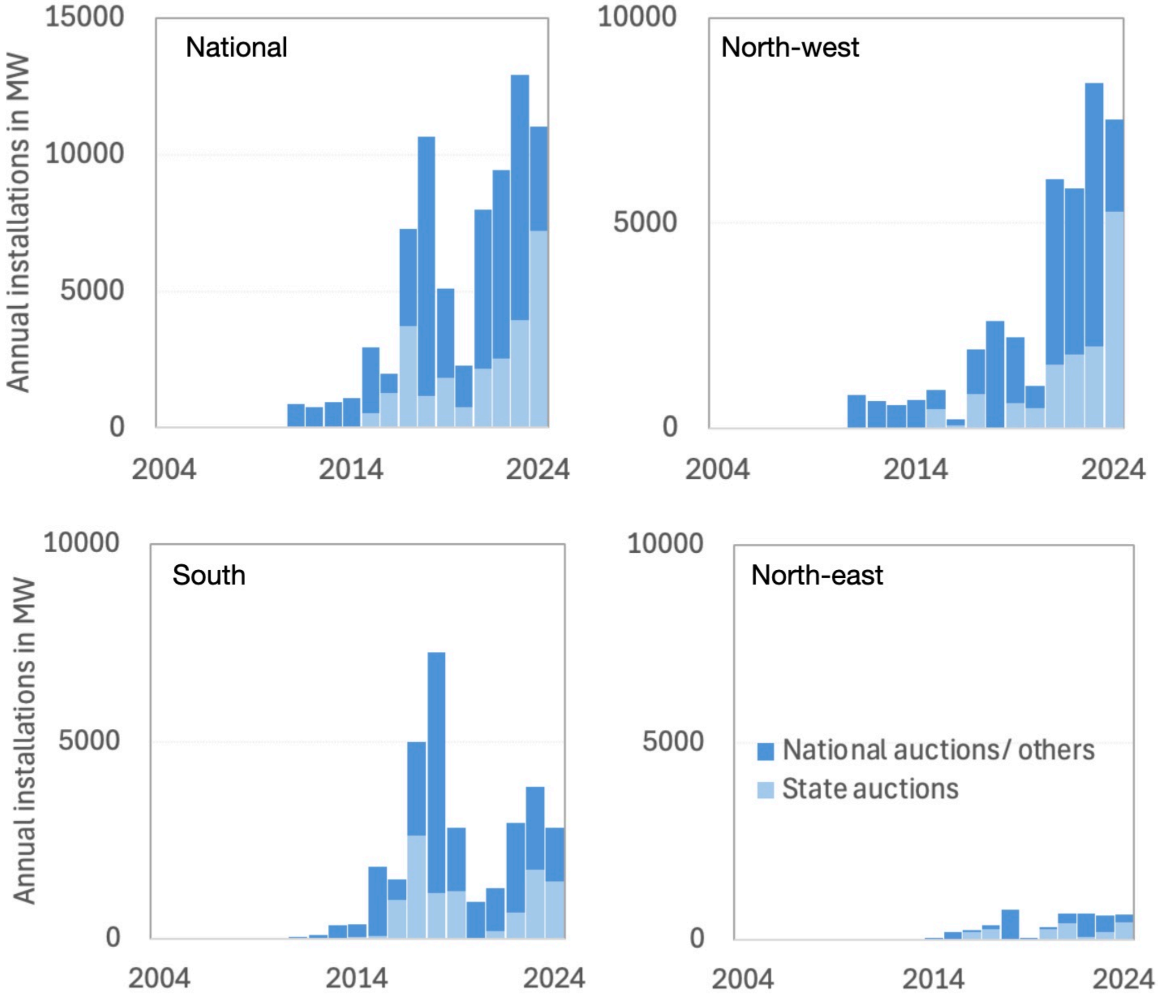

Figure 6.10: Capacity additions through auctions led by national and state off-takers, across regions.
"Others" include capacities added through FiT or auctions where the tendering entity could not be identified. These comprise a tiny share and have been included under the "national" category, as it was not possible to disentangle them. This output is based on my own calculation, assuming that allocated capacities in auctions are installed after two years. For state-specific outputs, refer to Figure A.12 in the Appendix.

Gujarat, Rajasthan, and Maharashtra. In Rajasthan and Maharashtra, most (if not all) auctions were linked to the agriculture-focused scheme, offering monetary incentives to developers (or farmers) for installing solar pumps and to DISCOMs for purchasing excess power. In contrast, some state DISCOMs, such as Tamil Nadu, conducted auctions that went largely under-subscribed. In other words, despite the cost decline, the ongoing policy effort mitigated emerging barriers.

The timing of these mutually reinforcing, co-evolutionary trends is noteworthy. The imposition of the import tax is politically motivated; it is hard to disregard the policy space created by declining technology costs. The import tax was introduced in 2018, shortly after U-parity (in 2017) was achieved. Achieving price parity meant any off-taker (either state DISCOMs or national entities) could foresee signing new solar contracts at prices comparable with other energy sources. When the import tax came in, auction tariffs stopped falling despite a reduction in technology costs (LCOE). The decline in technology cost was offset by the safeguard duty. See Figure A.13. As a result, the auction tariffs stopped falling post-tax despite LCOE declines (Figure 5.2). Had the import tax been imposed earlier, and auction tariffs stabilised before price-parity was reached, it would entail off-takers being locked into higher long-term tariffs above the average wholesale electricity price. With increased capacity additions, these higher tariffs would raise the financial burden, particularly exacerbating DISCOMs' woes, and also raising public expenditure (whether to bailout DISCOMs) or overburdening national institutions (offsetting prolonged state-level inefficiencies. Therefore, as technology grows, evolving socio-political paradigms require harder decision-making, but co-evolving techno-economic trends make such difficult and riskier/ disruptive policies to be undertaken. In short, economic improvements allow space for tougher policy adoption.

Strong momentum across the industry as a whole meant that it was able to absorb disruptions caused by political and external crises. For example, despite cost pressures, the industry showed resilience, with no significant drop in annual capacity additions, although the year-on-year growth rate declined. That said, much of this stability was supported by the national public sector enterprises. For instance, NTPC commissioned large capacities particularly in 2021-2022, SECI acted as a national-level off-taker (2018 onwards), and transmission infrastructure was built by central agencies (Green Corridor Policy 2015). However, this kind of strong intervention by the national government — especially under the Modi administration — is not unique to this phase. For example, in the formative phase, Gujarat led capacity additions when Modi was in power and pushed DISCOMs to sign high tariff contracts (Shidore and Busby 2019).

During the first half of the acceleration phase, which occurred after he joined the national office, growth in southern states like Andhra Pradesh and Karnataka occurred with national-state government coordination — both in terms of conducting auctions and installations (See Figure 6.10. Also in Busby and Shidore (2021)). Plus, the majority of the solar installations in Rajasthan have been led by central public sector enterprises (See Figure A.12 in Appendix). The key takeaway here is twofold. One, the Modi government again and again stands out as a key agent of diffusion. Two, given its limited resources, the national government, since 2014, has played a strategic, orchestrating role — intervening in a time-bound way, which has benefitted high-potential regions. In other words, high-potential areas with fewer barriers helped achieve faster growth with comparatively lower effort. In contrast, despite homogeneous policy effort (e.g., the start of pan-India auctions in 2018), low-potential areas with more complex challenges remained left out until better market conditions could support their resolution. This creates persistent spatial divergence in solar adoption across regions.

Throughout, coordination between national and state governments remained visible. In 2022–2023, national-led capacity auctions declined due to RPO finalisation delays and backlog clearance of power sale agreements. Plus, more ambitious policies were adopted. The national government introduced measures like the coal phase-down plan (replacing 30 GW with RE by 2025–26) and the national carbon credit trading scheme (2022). Collectively, these developments led to higher targets and a broader RE development approach during this period, reinforcing acceleration in solar growth, nationally.

6.4 Chapter summary

The aim of this chapter was to examine the role of policy effort in shaping utility-scale solar growth in India. To achieve this, I first analysed the institutional framework within which policy effort has unfolded. Second, I explored temporal and spatial variation in policy effort across governance levels, focusing on evolving targets and the adoption of specific policies. Finally, I assessed how these efforts co-evolved with technology growth, cost declines, and political change.

While vertical unbundling has advanced in India's power sector, horizontal unbundling remains limited, largely confined to generation. This has produced three key actor types in the Indian solar landscape, each with distinct motivations, capacities, and attitudes towards policymaking. First, private entities, including developers and domestic component manufacturers, operate independently and have gained prominence through recent market reforms. Their outlook is heavily shaped by profit maximisation. Second, national and state policymakers play an integral role. Those at the national level possess stronger institutional capacity, including technical expertise, advisory bodies, and financial resources, and set overarching targets and frameworks. State-level policymakers are responsible for the coordinated implementation of national objectives. Their capacities vary with bureaucratic strength, technical knowledge, and institutional support. Policymakers' outlook is influenced by political priorities and long-term sector planning. Third, state-owned enterprises function as intermediaries and act as policy implementing agencies. They own the majority of sector operations, operate commercially within financial and technical limits, and engage with private actors. Their objectives are to ensure a reliable supply and, preferably, remain financially viable.

With regards to the evolution of policy commitments, I found that India's solar targets have evolved with the national government coordinating and setting the directions while states play increasingly active roles, though unevenly. Early targets were solar-specific and nationally mandated, while post-2022 targets have broadened to include other RE technologies, with solar still central. Nationally, solar targets have been continuously raised, and capacity addition has seen persistent acceleration. Sub-nationally, the relationship between targets and actual capacity additions is highly uneven. Some states continue to ratchet targets upward, while others — across both high- and low-growth regions — have stalled or reduced them. Ratcheted targets and actual capacity addition are concentrated in southern and northwestern states, whereas the north-east and parts of the north-west remain under-prioritised, revealing a growing regional divide.

With regards to actual policy actions, the policy mix has expanded despite declining technology costs and solar achieving different types of cost competitiveness. The number and variety of policies have grown in response to emerging socio-technical and political barriers. While many of these challenges are shared internationally, issues such as grid expansion and system integration emerged earlier in India, whereas domestic manufacturing policies emerged later at advanced stages of growth. Throughout, policies supported not only technological growth but also the regulatory, institutional, and infrastructural capacity needed to manage that growth. New policies are layered atop older ones, and national and state governments share broad priorities but implement them using a different set of instruments. More policies do not always translate into higher adoption. However, states with stronger uptake have focused policies on land acquisition and system integration. Even as solar becomes more technically and economically viable, financial incentives remain critical, though the extent of this effort in monetary terms remains unknown.

Finally, policy effort co-evolved with technological growth, cost decline, political shifts, and external factors, including global policy trends and external crises. This co-evolution is reflexive and iterative, producing non-linear trajectories. Policies helped accelerate growth but also introduced setbacks. Cost decline helped buffer negative effects and enable riskier policy adoption. In other words, techno-economic maturity created space for politically feasible and economically tolerable policy change. Politics plays a crucial mediating role: policy decisions are not purely technocratic responses to market signals or socio-technical challenges — they reflect political calculations, institutional capacity, and leadership priorities. The Modi government's strategic, orchestrating role is emblematic of this, initially in Gujarat during the early growth phase and later through national entities like SECI and NTPC. These interventions bypassed weaker state DISCOMs, maintained momentum during rising costs and investment risks, and undertook critical infrastructure development. However, this approach contributed to spatial divergence, with high-potential regions prioritised to optimise resources, while regions with lower solar potential and coal reliance were de-prioritised. Early phases of technological growth are therefore not free from constraints; instead, more complex challenges are deferred until market conditions can effectively address them.

7. Discussion

This chapter is structured around four main sections, each of which aligns with a key component of the dissertation's overall contributions. In Section 7.1, I revisit the rationale and contextual background that shaped the two central puzzles and four research questions addressed. In Section 7.2, I outline the methodological and conceptual contributions, detailing how the research design and analytical approach were developed to engage with these puzzles. Section 7.3 presents the empirical findings around the four research questions and the broader significance of these findings. Finally, in Section 7.4, I reflect on how each of the four central research questions has been addressed, identify key limitations associated with them, and highlight potential directions for future research.

7.1 Revisiting the gap

The main goal of the dissertation has been to understand the relative role of market advantage and policy effort in accelerating RE technologies in developing countries. So far, two debates have shaped the uncertainty around this question. Each presents a market-driven view that focuses on techno-economic factors, and a policy-driven view that emphasises on socio-political factors. Both views encompass a wide range of positions on the factors' relative strength in sustaining RE acceleration.

The first debate concerns the role of cost decline and policies in driving RE growth over time. The market-driven side argues that policy support is essential in the early stages to absorb market failures, drive innovation, and bring down technology costs (Jaffe et al. 2005; Owen

2006; Stern 2007). As costs decline, the self-sustaining attributes of the technology unlock, and the need for active policy support diminishes (Creutzig et al. 2017; Liñeiro and Müsgens 2025; Victoria et al. 2021). The policy-driven side, on the other hand, argues that once RE technologies become economically viable, they face non-cost and deeply socio-technical and political barriers (Köhler et al. 2019). This is because RE technologies are structurally and operationally incompatible with existing regulatory, societal and infrastructural setups (Blazquez et al. 2020; Christophers 2024). As a result, recurring market failures or system failures occur (Bergek et al. 2008; Negro et al. 2012; Woolthuis et al. 2005), which are not captured solely through a technology cost-focused lens. Therefore, as technology grows and costs fall, continued and adaptive policy support remains necessary. No longer to reduce technology costs, but to overcome barriers like grid integration challenges (Markard 2018; Ollier et al. 2024), land-use constraints (Frantál et al. 2023; Susskind et al. 2022; Ven et al. 2021), and resistance from incumbent actors (Breetz et al. 2018; Jacobsson and Lauber 2006).

The second debate concerns the role of cost decline and policies in driving RE growth across space, especially from technology-pioneers to technology-recipient countries. Here, the market-driven view suggests that recipients can benefit from technological and policy learning in the pioneers, and therefore can bypass the need for a similar level of policy effort as in the pioneers (Arndt et al. 2019; Bogdanov et al. 2021; Gulagi et al. 2022). Rooted in the mainstream diffusion-of-innovation literature, this debate has more recently been framed around the idea of "technological leapfrogging," where developing countries can bypass traditional development pathways and directly adopt advanced energy technologies (Goldemberg et al. 1987; Murphy 2001). The policy-driven side challenges this stance, arguing that various contextual shortcomings that delayed the introduction of renewables in the first place, such as a higher risk of financing, require sustained policy effort (Comin and Hobijn 2010b). This argument aligns with the various criticisms of leapfrogging (Ameli et al. 2021; Fu and Zhang 2011; Gallagher 2006; Yap et al. 2022).

Together, these two debates reflect a broader disconnect among academic disciplines and traditions. On one side are environmental and energy economists, typically rooted in neoclassical economic thinking, representing the market-driven view. Their work often produces macro-level, quantitative outputs intended to generate generalisable insights for policymakers. This tradition forms the foundation of widely used tools, such as Integrated Assessment Models (IAMs), prominent at the science-policy interface. Over recent decades, IAMs have expanded in scope and influence, driven by increasing policymaker demand for data-driven projections and advances in modelling capabilities (Beek et al. 2020). However, IAMs have faced criticisms for their narrow focus on techno-economic cost optimisation, often overlooking the complex and dynamic interactions between technology, costs, policy, and politics (Geels et al. 2016; Jewell and Cherp 2023; Trutnevyte et al. 2019).

On the other side are scholars primarily from innovation studies, political science, and also from geography, and newer economic traditions, who represent the policy-driven view. They argue that energy transitions are not merely economic processes but are deeply embedded in socio-political contexts (Ameli et al. 2021; Bergek et al. 2008; Geels et al. 2016; Jewell and Cherp 2023; Trutnevyte et al. 2019). Here, scholars have sought to bridge the gap between technology and policy co-evolution by mapping feedback loops - both positive and negative - arising from multiple sources Ayoub and Geels (2024); Edmondson et al. (2019); Gao and Yuan (2020). See Section 2.2.1. However, their work is often qualitative and grounded in specific contexts. Some others have proposed to move beyond a bridging strategy altogether. They call for a merging strategy, which entails building new types of models where "key societal factors can be modelled" (Trutnevyte et al. 2019). However, the application of this type of work remains limited (Hirt et al. 2020).

Other quantitative studies in this tradition have focused on particular policy instruments (e.g., carbon pricing, subsidies, feed-in tariffs), clusters of instruments, or broader attributes of policy mixes, such as stringency, sequencing, diversity, and density. These have then been linked to specific climate outcomes, including technology growth. Therefore, a sufficiently integrated approach to policy evolution remains missing. Plus, much of this research concentrates on developed countries and frequently overlooks the distinct realities faced by technology recipients, who are expected to drive most of the future RE deployment.

Thus, beyond theoretical disagreements, the two empirical debates expose important methodological gaps. First, a lack of systematisation: while considerable progress has been made in understanding the co-evolution of technologies, costs, and policies, we still lack a holistic and integrated perspective that captures how these dynamics unfold across the different stages of technology growth and diffusion. Second, there is limited comparability across institutional contexts. Much of the existing knowledge is derived from studies in developed countries, leaving questions unanswered about the co-evolutionary process at the periphery of global innovations.

7.2 Conceptual and methodological contributions

I addressed these gaps by integrating concepts and methods from both the market-driven and policy-driven views. I did so in three steps. First, I developed a conceptual framework grounded in the three perspectives of studying national energy transitions (Cherp et al. 2018). Within the techno-economic perspective (Chapter 5), I examined the evolving cost competitiveness of solar projects, capturing the market drivers of solar growth. Within the political perspective (Chapter 6), I analysed changes in policy ambitions, regulatory frameworks, and shared governance responsibilities between national and state entities, reflecting the policy drivers of solar growth. Across Chapters 4, 5, and 6, I engaged the socio-technical perspective, exploring how costs and policies together influence social actors who, in turn, shape solar growth. In short, I offered an integrated, time-series, and multi-scalar understanding of the dynamic complexities of co-evolution of systems, popularly studied through the three perspectives. See Figure 3.6. Second, I demonstrated a semi-quantitative operationalisation of this framework that mapped developments around costs and policies against the acceleration of a RE technology, in a developing country context. In doing so, I went beyond earlier attempts, like (Bhatia 2023), that remained limited to the conceptual synthesis of literature. The operationalisation included four main pillars.

From a techno-economic perspective, I looked at how past policies shaped costs. To do so, I calculated the evolution of the absolute and relative cost of solar electricity generation. Absolute cost captured the levelised cost of electricity (LCOE), defined purely as a techno-economic metric, decoupled not only from policy interventions but also from the market prices of selling solar electricity. LCOE reflected technology learning and was calculated bottom-up, combining national cost assumptions with state-specific performances. Relative cost, in contrast, situated LCOE against four other costs and electricity prices, borne by different actors in India's electricity market. Here, I drew on but adapted the concept of grid parity to fit a regulated power sector context. The adaptation helped address some of the criticisms of calculating grid parity and equate it to the notion of cost competitiveness, as something plural, temporally and spatially dynamic, and actor-dependent. (See Section 2.3.2)

From a political perspective, I looked at how policy effort evolved based on cost decline and technology growth. To do so, I calculated the evolution of policy effort based on solar targets and the density of policy actions. To map the evolution of targets, first, I created a database of national and state-specific targets from 2010 through 2030. Then I examined their timing of adoption, temporal and spatial spread, and level of compliance. Targets reflected policy ambitions and planned near-term technology development patterns based on policymakers' perceived feasibility of solar. Additionally, I assessed the density and diversity of the active policy mix, taking into account policy adoption and policy termination over time, disaggregated between federal and state governments. This involved: (a) integrating the two typologies of policy classification - policy priorities and policy instruments - within a single study (which, to the best of my knowledge, is a first in the technology-policy co-evolution literature); and

(b) developing and applying an original classification system that captures the shifting policy priorities along the path of RE technology growth. A classification based on priorities allowed mapping the types of barriers that arise at different stages of technological growth, serving as a proxy for feedbacks between politics, policy, costs, and technology. A classification based on policy instruments, in parallel, revealed how these priorities are addressed by the policymakers. Plus, I offered a disaggregated view of effort between national and subnational policymakers, not simply in administrative terms, but also as agents of targeted and distributed intervention across different policy domains. See Section 3.2.3.

From a socio-technical perspective, I looked at the relative role of cost decline and policy effort in shaping actors' behaviour, subsequently influencing technology growth, and vice versa. I calculated technology growth, first by selecting 18 Indian states that have contributed to nearly 100% of national deployment. I then examined the pattern and phases of solar growth within each state, and national growth as an aggregation of state-level contributions. I built on prior studies that analysed the influence of geography, socio-economic and socio-political conditions, by embedding this within the contextual background of cost-policy-technology co-evolution. Finally, I calculated the changing behaviour of actors involved - both private and public - based on changes in their behaviour as a result of cost decline and policy effort. Particularly, I looked at solar developers' (segmented by market share) ability to install/commission new solar projects, and solar off-takers' (segmented by state and national ownership) ability to contract new solar through solar auctions. See Sections 3.2.1.

I interpreted causal links among systems studied across three perspectives through process tracing. This involved: (a) adopting a mechanistic view of social phenomenon, which argues that there are identifiable and recurring links between cause and effects, despite the contingent and path-dependent nature of energy transitions; (b) applying prospective process tracing, where establishing linkages is guided by theory-based hypothesis testing, and retrospective tracing, where failure to explain unexpected outcomes help uncover new mechanisms; (c) constructing time-series visualisations to map the temporal sequencing of events across three systems; and, (d) testing the robustness of causal claims through counterfactual reasoning over time and contexts. See Section 3.2.4.

Finally, I applied the conceptual and analytical framework to the context of utility-scale solar in India. Both as a champion of solar energy and a technology-recipient country, the Indian case allowed for examining the relative role of costs and policies in driving technology growth and diffusion over time and space. As a developing country with rapidly growing energy demand and rising risk of carbon lock-in, India also represented an important site for decarbonisation, where understanding the relative role of policy and non-policy factors remains crucial. Ultimately, India's federal structure allowed for a comparative analysis of not only developments across national and state levels but also in testing the generalisability of findings across contexts.

7.3 Empirical findings and contributions of research

The goal of this dissertation has been to investigate four central research questions. (i) What is the relative role of market advantage and policy effort in driving solar deployment? (ii) How do policies evolve in response to increasing levels of solar deployment? (iii) As a technology-recipient and developing country, what barriers emerge at different levels of solar deployment in India? and (iv) How do policies influence the diffusion of solar among early and late adopters within India? These questions collectively engage with the two empirical debates that frame the rationale of my research. The first two are concerned with the temporal dynamics of renewable energy growth — specifically, the relative role of declining costs and evolving policy effort over time. The latter two focus on the spatial dynamics of the deployment — first at the national level (as a developing, technology-recipient country) and then at the subnational level (across early and late adopting Indian states), asking how evolving costs and policy effort interact to shape patterns of convergence or divergence. This section consolidates the key findings of the dissertation, organised around these four research questions.

What is the relative role of market advantage and policy effort in driving solar deployment in India ?

Despite its strong market advantage, the acceleration of utility-scale solar in India has, and continues to remain, overwhelmingly policy-driven. The country has benefited from the transfer of technological innovation and the early years of policy learning from pioneering countries. Additionally, India benefits from abundant solar resources, rapidly growing electricity demand, and substantial declines in the cost of solar electricity generation. These factors, in theory, should have enabled self-sustaining growth once costs declined and parity points were achieved. Yet, the trajectory of cost and policy evolution when mapped on the trajectory of solar deployment suggests otherwise. Policies continued to play a central and enduring role, despite the technology's growing competitiveness.

The last one and a half decades have seen several positive, mutually reinforcing global and domestic mechanisms (e.g., global technology learning, targeted policy interventions, and a competitive domestic solar auction programme). These have not only brought down the cost of producing solar electricity but also made solar increasingly competitive against other energy sources. In Chapter 5, I observed the achievement of three (out of four) anticipated parity points. Nationally, in 2017, solar auction tariffs reached parity with the wholesale electricity price (U-parity), meaning solar off-takers could hereon contract new solar capacity below the national average of contracting new electricity generation from other energy sources. In 2021, the cost of producing solar electricity reached parity with the wholesale electricity price (or S-parity), meaning hereon, it was not only cheaper to contract new solar but also build new solar than the price of electricity at the grid. In the same year, for state DISCOMs, the power purchasing cost of solar reached parity with that of coal (C-parity), even when accounting for legacy contracts, rendering DISCOMs more financially flexible in their operations. The picture at the subnational level was slightly varied. U-parity occurred uniformly at the same time due to the surge in pan-India auctions from 2018, which theoretically allowed the flexible siting of contracted capacity. In contrast, S- and C-parity were reached unevenly across states influenced by local factors, such as solar irradiance, land availability, and the size of high-cost legacy solar PPAs. See figures 5.4 and 5.6.

The market-driven stream of literature suggests that once these parity points are reached, the technology can self-sustain. My findings show otherwise. Following U-parity, installations briefly accelerated, but slowed down very quickly — a pattern visible across the country, but one that lasted for varying durations among states. Soon after, when S- and C-parity were achieved, national deployment rates merely stabilised rather than recovering to previous acceleration rates. Additionally, when verified against regional trends, the misalignment between deployment and parity achievement was stronger. In the north-west, installations grew despite solar not reaching parity with coal. In contrast, the south and north-east achieved parity with coal, yet deployment slowed in the former and did not change in the latter. These patterns highlight the insufficiency of cost decline alone to accelerate RE technology growth. On the other hand, my findings in Chapter 6 reveal the evolution of an expansive and diverse active policy mix that closely aligned with technology growth trends at the national and sub-national level.

Consistent patterns evolved when mapping public (more inclined to implement policy) and private (more inclined to respond to market signals) actors' behaviour against cost evolution. Almost all existing privately-owned solar developers slowed new installations after 2018 and reduced their participation in auctions (Figure 5.8), despite achieving U-parity one year ago. This phenomenon was most notable and persisted longer in the southern states, which had previously led solar development (Figure 4.1). The decline occurred due to growing concerns over payment delays from financially volatile state DISCOMs. In other words, despite growing competitiveness, barriers associated with profitable return on investment outweighed the attractiveness of investing in low-cost solar electricity production. In response, public enterprises, operating as implementing agencies for policymakers, stepped in. Yet, the intensity and coherence of these efforts varied across states and between national and state actors.

Among state-level DISCOMs, procurement behaviour did not consistently align with parity events. For instance, many early adopters (especially in the south) retreated from conducting auctions post U-parity, while less active states (both in the south and north-west, such as Gujarat, Maharashtra, and Rajasthan) scaled up their solar procurement after 2018. In contrast, national entities such as the Solar Energy Corporation of India (SECI) and the National Thermal Power Corporation (NTPC) responded more systematically, both in terms of conducting auctions and installing solar capacity. See Figures 5.9 and 5.8. Beginning in 2018 (post U-parity), they significantly increased awarding auctions, and also again in 2023 following the attainment of S- and C-parity. These actions were less motivated by improved cost-competitiveness, but rather reflected deliberate efforts to stabilise deployment amid weakening investor confidence, coupled with policy and market shocks converging at the same time.

Taken together, my findings reveal three key points. One, they call for a reassessment of the assumption that cost-competitiveness naturally leads to market-driven RE growth. The Indian utility-scale solar case shows that achieving cost competitiveness did not lead to an automatic, self-reinforcing deployment trajectory. Two, they call for an honest understanding of the policy effort needed to drive RE growth. The Indian utility-scale solar case showed that policy effort did not taper with cost decline, but rather it intensified and diversified. Three, they call for understanding how national policy efforts might be distributed across governance levels. The Indian utility-scale solar case showed that when the capacity of subnational actors reached its limit, national policymakers, through their publicly owned enterprises, stepped in.

How do policies evolve in response to increasing levels of solar deployment in India?

In Chapter 6, I mapped the co-evolution of policy alongside the acceleration of utility-scale solar growth in India. It illustrated that sustaining deployment at scale requires an expansive, diverse, and increasingly complex policy mix. While the evolution of this mix reflects the broader, non-linear, and partly semi-autonomous co-evolution of techno-economic, socio-technical, and political systems, several key patterns emerge. These offer new insights into feedbacks commonly studied within the technology-policy co-evolution literature.

First, while policies enable technological growth, that very growth generates demand for new policies. Throughout politics and external factors interfere. See literature Section 2.2.1. Previous studies on technology-policy co-evolution have offered a general understanding of how this co-evolution might look, identifying different policy needs (Ollier et al. 2024) or political rationales (Breetz et al. 2018) at different stages of technology growth. My work offers a more systematic, holistic, and somewhat generalisable representation of barriers that policies address on the path of RE technology growth. See Figures 6.6 and 6.7. See also work by **?**. In doing so, I disentangled the more generalisable technology-specific barriers (e.g., market creation, domestic manufacturing, system integration, complementary technologies, land use and public acceptance) from the political (e.g., the rise of political entrepreneurship, and regime change) and external context (e.g., the COVID-19 pandemic, international trade conflicts, and supply chain disruptions) against which they evolved. See table 6.3. I also quantitatively show that policies are rarely aligned neatly across the technology lifecycle but that older policies often persist alongside newer ones - an aspect, examined in the policy change literature, reflecting factors like decision-making uncertainty, bureaucratic inertia, and policy lock-ins. For example, see (Fernández-i-Marín et al. 2024).

Second, I demonstrate how the structure and density of the active policy mix evolve and vary across governance levels. Previous studies specific to India have noted that the national government typically sets broad agendas, while states adapt and implement policies based on local conditions (Bhatia 2023). My research confirms and extends this finding. National policies are generally more diverse, addressing a wider array of issues. State-level policies, on the other hand, focus more narrowly on issues like system integration and land use, reflecting both their jurisdictional scope and operational responsibilities. See figure 6.8. While past work, like (Shrimali et al. 2020), links policy variation across states to spatial divergence in solar growth, I find no strong correlation between the overall density of a state's policy mix and its deployment levels. This may reflect differences in analytical approach. I emphasise density, while Shrimali et al. (2020) focuses on stringency. That said, I do observe a moderate positive correlation ($R^2 = 0.51$) between solar adoption and policies targeting system integration and land use (Figure A.9). However, causality remains unclear on whether such policies may either respond to increased deployment or help enable it.

Third, I find that national-level policy changes align with clear pulses in solar growth (also in). In other words, changes in the policy mix can both drive and constrain technological expansion. For instance, the surge in system integration and complementary technology policies in 2021 coincided with renewed solar deployment. In contrast, the 2018 introduction of domestic manufacturing policies, particularly import tariffs, was followed by a slowdown in 2019, later exacerbated by the pandemic in 2020, and raw material shortages through 2022. So the question is — why do such policies get adopted, and how do policymakers navigate these negative impacts? I find that costs and policy interactions are central to understanding these non-linearities. While cost decline alone does not sustain growth, it influences policymaking, which in turn influences technological growth.

For example, cost improvements reshaped the configuration and capacity of key actors. Early-mover DISCOMs, especially in southern India, which helped drive down costs and auction tariffs through aggressive procurement, were subsequently locked into expensive PPAs. Financially constrained, they pulled back from further auctions, slowing growth in the region. This dynamic is emblematic of the feedback loops explored in the policy-technology co-evolution literature - where policies that enable quick market gains can create institutional burdens (Edmondson et al. 2019) and ultimately lower technology deployment. Also see Figure 5.9. At this point, national off-takers stepped in. Among developers, larger firms leveraged their economies of scale and financial strength to withstand competitive pressures in the early years and policy shocks later on. In contrast, many smaller players exited the market. See Section 5.3.1. Post-2017, as auction tariffs stabilised, a new wave of smaller developers emerged, particularly in the commercial and industrial segment, when the achievement of cost-parity (S-parity) made self-generation economically viable. Larger firms, in the meantime, like the Adani group, leveraged their market position to influence policymaking to introduce an import tax on solar cells and modules.

Another commonly studied feedback in this literature is that — once a niche industry grows, it is better positioned to lobby for supportive policy. However, their growing market share soon challenges the incumbent regime, requiring a renegotiation of institutional arrangements arbitrated through policies (Breetz et al. 2018). Two implicit assumptions underpin this view: (i) that growing economic viability of the niche industry will attract aligned coalitions towards it around the common goal of accelerating technology growth; and (ii) that contestation primarily arises between incumbents and niche industries. However, in the case of solar in India, I observe that actors within the niche industry pursued their interests, which diverged from the common goal of accelerating growth. As a result, contestation arose not across, but within the (niche) industry itself. As solar became more profitable, domestic manufacturers without scale advantages (compared to solar developers) intensified lobbying for protectionist measures. After several failed attempts and a WTO ruling against local content requirements in solar auctions, a successful effort led by the Adani Group (then the developer with the highest market share and the only one with domestic manufacturing capacities) led to the 2018 import tax on solar modules and cell imports. This protectionist shift, while advancing long-term industrial development, was widely opposed by other developers and contributed to a short-term slowdown in growth. See Section 6.3.3 and Figure 6.9.

Nonetheless, this disruption did not last long, as many had predicted. It was offset by a sharp increase in national off-taker-led auctions, following a 2017 policy that offered developers reliable, steady demand and credible buyers. See Figure 5.9. Even as the cost of producing solar electricity rose and auction tariffs plateaued (due to the imposition of the import tax), solar maintained competitiveness with the wholesale electricity price, having achieved U-parity shortly before. This had two implications. One, it preserved solar's attractiveness for public off-takers. Two, it illustrated that while cost decline expanded the policy space to make politically hard decisions, it did not substitute for sustained policy support. My finding, therefore, aligns with previous research arguing that falling costs enable more ambitious policy efforts (Meckling et al. 2017; Pahle et al. 2018) and reduce the public spending per unit of support (Way et al. 2022). Similar evidence, on cost decline providing policy space, also emerges across time in the Indian solar case. For example, a steep cost decline preceded the 2015 upward revision of the 2022 solar target (alongside political motivations behind it). The achievement of S- and C-parity in 2021 closely coincided with the announcement of ambitious 2030 RE goals. Major initiatives like the coal phase-down plan (replacing 30 GW with RE by 2025–26) and the national carbon credit trading scheme (2022) also followed these market shifts. While part of these developments align with national governments following global policy trends (e.g., uptick in global climate action, the EU's upcoming Carbon Border Adjustment Mechanism), they are grounded in growing confidence in solar/renewables underlying techno-economic improvements.

Taken together, my findings reveal three key insights. One, technology growth is non-linear and shaped by its co-evolution with costs and policies. Looking at the co-evolution of the policy mix alongside cost decline and technology growth can be a good way of understanding these interdependencies. Two, the policy mix becomes more complex as deployment increases, reflecting greater policy effort alongside technological growth. However, not all policies are unequivocally supportive. Market shifts reconfigure actor dynamics, and new winners may pursue goals that diverge from the collective interest in accelerating deployment. Third, while declining costs and growing cost competitiveness enable more ambitious and flexible policy-making, they do not substitute for sustained policy support to maintain acceleration.

What barriers emerged at different levels of solar deployment in India ?

As discussed previously, there is a consensus in the literature that new barriers arise as RE technology grows, necessitating corresponding shifts in policy focus (Section 2.2.2). However, existing insights into the sequencing of these barriers, on top of being less systematic, are largely derived from the experiences of pioneering countries. The case of utility-scale solar in India offers a contrasting perspective from a technology-recipient, developing country. By comparing my findings with those from the broader technology-policy co-evolution literature, including concurrent research on onshore wind in Germany using the same classification scheme (**?**), I situate the emergence of these barriers relative to those experienced in technology pioneers. India's solar rollout diverged significantly from this trajectory. Integration barriers surfaced much earlier, while industrial policies appeared later and in a more disruptive manner. These deviations had direct implications for how global, technology-induced cost declines influenced the rollout, as well as for the level and timing of domestic policy effort that was necessary to accelerate solar adoption. More broadly, my findings challenge the optimistic assumptions of the technological leapfrogging literature, which suggests that recipient countries can easily adopt technologies through transfer from pioneering countries with comparably less policy effort.

First, see Figure 7.1, core integration barriers, both into non-physical electricity systems (addressing electricity market readiness) and physical infrastructure (addressing grid readiness), emerged at very early stages of solar deployment. For instance, curtailment protection policies were introduced as early as 2010, when solar contributed literally 0.0% to the electricity supply. The Green Corridor policy, aimed at increasing transmission capacity to accommodate a growing share of renewables, was launched in 2015, shortly after solar achieved national take-off and reached 0.6% market share. Efforts to promote hybridisation with wind and battery storage began in 2017 (coinciding with grid parity), when solar constituted just 2.1% of the electricity mix. Notably, policies allowing greater private sector participation were initiated as early as 2003, more than five years before the first national solar policy, and have continued to expand as part of broader power sector liberalisation efforts. In contrast, for Germany's onshore wind, comparable system integration policies did not emerge until 2004 (**?**), when wind already accounted for 4.2% of total electricity generation. This comparison shows that developing countries might need to front-load integration efforts due to infrastructural limitations. While RE deployment requires systemic transformation in any context (see section ref), the challenge is particularly acute in developing countries where the foundational grid and market systems that must be transformed are not yet ready. This finding echoes concerns raised by international agencies regarding the fragility of India's grid (IEA 2021c), those by market observers who note the persistent need for curtailment protection to ensure project viability (Rao and Agarwal 2021), and the emerging trends of plunging spot market prices (BridgeToIndia 2025).

Second, domestic manufacturing and industrial policy in India emerged later (Figure 7.1). While a local content requirement in solar auctions was introduced as early as 2010, substantial manufacturing support only began ramping up from 2018. By then, solar had already reached 2.8% of market share. In contrast, for onshore wind in Germany, domestic manufacturing support was introduced before technological adoption, and was gradually phased down after achieving take-off. See also **?**. Literature shows this to be an attribute typical of technology pioneers, where the formative stage is R&D focused (Hansen et al. 2018). The Indian solar case reflects a broader structural pattern common to technology-recipient countries, where initial policy efforts tend to prioritise rapid adoption and cost-competitiveness over local supply chain development (Awate et al. 2012; Buckley et al. 2020; Fu et al. 2011). When countries

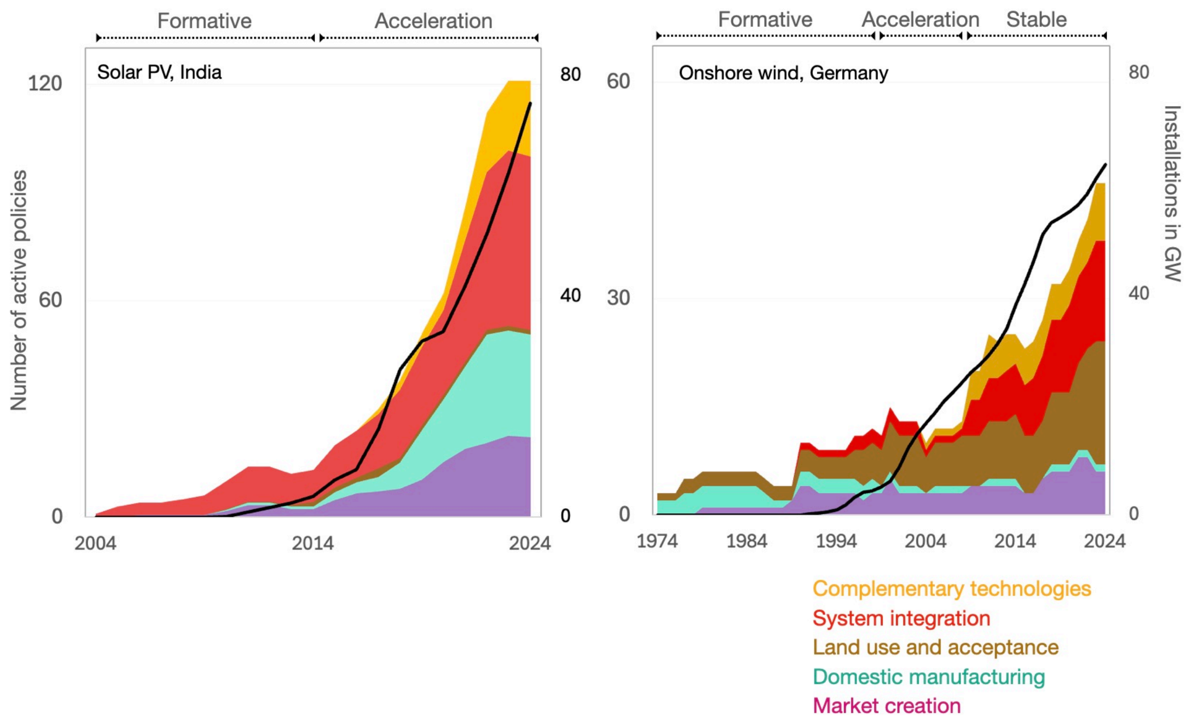

Figure 7.1: Changes in the national active policy mix: Solar PV in India versus onshore wind in Germany.
Data on policies and technology growth phases in Germany is from **?**.

do succeed in building out local supply chains, as in China's case with solar, such outcomes are typically the result of deliberate, substantial, long-term policy experimentation and effort (Fu and Zhang 2011). By contrast, India's innovation and industrial policy lagged behind initial deployment and only became prominent after solar reached a certain market share, and social actor configuration mixed with the political landscape allowed for lobbying efforts to shape policy in this direction (Behuria 2020). Missing the early window for developing domestic supply chains limited India's ability to later pivot toward industrial policy without trade-offs. For example, the imposition of import tariffs in 2018 on foreign modules and cells led to a slowdown in solar deployment. Therefore, my findings challenge the optimistic view of conventional leapfrogging and instead support the transformative view (see Section ref), which argues that successful technological transfer — crucial for leapfrogging — requires proactive, deliberate efforts to build institutional and infrastructural foundations that can integrate these transfers into local systems, rather than assuming they will take root organically (Schmidt and Huenteler 2016; Yap et al. 2022). This aligns with longstanding insights from the trade and innovation literature, which emphasise that catching up in fast-moving technologies is not only costly but increasingly resembles a "moving target" problem. That is why countries race to position themselves in the front before technological advantage locks in. Similar dynamics are seen for the case of the electric vehicle industry, where Europe's recent drive to scale battery manufacturing lags behind China's decade-long head-start (Pandey 2025), and in the ongoing global competition around leadership in Artificial Intelligence (Araya 2019; Hagiu and Wright 2025).

In sum, my findings point to two main insights. One, while RE uptake in developing countries faces many of the same barriers seen in wealthier, technology-innovating nations, the sequencing of these barriers does not follow the same path. In the Indian utility-scale solar case, integration challenges emerged earlier, while domestic manufacturing was postponed and had disruptive effects on technological momentum. Each ultimately increased the level of policy effort required and couldn't be absorbed by the cost decline and growing market advantage. Two, viewing technological leapfrogging as a low-effort shortcut misrepresents the policy intensity needed to sustain RE acceleration in developing contexts. The sequencing of policy priorities (or barriers) in the Indian utility-scale solar case points towards the need for high policy effort.

How do policies influence the diffusion of solar among early and late adopters within India?

The spatial diffusion literature presents three conflicting positions. See section ref. The first, aligned with the optimistic "leapfrogging" view, argues that technological learning advantages dominate. Late adopters benefit from knowledge spillovers and accumulated global experience, enabling them to grow faster than early adopters and ultimately catch up. The second position emphasises contextual disadvantages. It contends that the same structural barriers that delay initial adoption also impede subsequent growth, leading to persistent divergence. The third view offers a balancing perspective. Positive learning effects and negative contextual factors offset each other, resulting in similar growth rates across adopters, and yet no evidence for convergence. In other words, the latter two views challenge optimistic leapfrogging. My findings from utility-scale solar in India support the divergence argument. Examining both historical trends (e.g., timing of adoption and growth rates, technology-policy co-evolution) and planned trajectories (e.g., state-level targets), I find spatial divergence between early and late adopters has been and continues to remain persistent within the country in the near-term.

First, from a technological standpoint, in Chapter 4, early-adopting states were the primary drivers of national solar growth. Most southern and northwestern states were early adopters. Among them, some (e.g., Rajasthan and Gujarat in the north-west) have continued accelerating, while others (e.g., Maharashtra in the south) experienced a period of stagnation before resuming acceleration recently. In a few cases (e.g., Madhya Pradesh and Punjab in the north-west, and Karnataka, Andhra Pradesh, and Telangana in the south), acceleration was brief and growth has been stagnating in them for a while. Meanwhile, late-adopting states, particularly those in the north-east, have shown no signs of catching up. While there is a positive correlation between the timing of take-off and the maximum growth rate, it is statistically insignificant (see Figure 4.4). My findings in this regard align with the balancing view in the spatial diffusion literature — while late adopters may benefit from accumulated learning, these advantages are counteracted by the structural disadvantages they face. As a result, maximum growth rates appear broadly similar, though absolute deployment levels remain highly uneven. What emerged is a regionally differentiated picture, where deployment alternated between the north-west and southern regions, while the north-east remains almost absent from the national solar landscape.

Second, incorporating the cost and policy lens, in Chapters 5 and 6, I find that the underlying causes of these spatial patterns are the result of cost-policy-technology co-evolution. The evidence points to a semi-autonomous and thus asynchronous feature of this co-evolutionary process. In a context where policymakers face competing priorities, resource constraints, uncertainties, and institutional limitations, decision-making often becomes incremental, reactive, or fragmented — a process Lindblom (1959) famously described as “muddling through,” and which Hoppmann et al. (Hoppmann et al. 2014) characterise as leading to “compulsive policymaking.” As previously evidenced, this process resulted in phases of misalignment, when policy ambition outpaces system readiness, or when industrial imperatives conflict with deployment priorities. Moreover, policies aimed at continually leveraging market gains by unlocking or reinforcing positive feedback loops exacerbated spatial inequalities, particularly when feedbacks were not deliberately calibrated. (Some would argue that this reflects the absence of equity as an explicit policy objective (Yap and Truffer 2019), which would otherwise necessitate additional policy effort.) For instance, when the 2018 import tariff increased the cost of solar electricity production for developers, national auctions helped mitigate risks by offering guaranteed demand and a financially credible off-taker. Yet, despite their pan-Indian design, developers overwhelmingly concentrated projects in high-return states such as Gujarat and Rajasthan. Against a background of nationally coordinated solar expansion geared toward ambitious targets, policymakers appeared to optimise resource allocation by prioritising high-potential regions rather than ensuring equitable diffusion. This is not to suggest that leading regions faced no barriers, but rather that stronger market advantage here enabled them to absorb and manage these challenges more effectively. By contrast, regions with lower solar potential presented more complex challenges, which appeared to be strategically deferred (permanently, or) until more favourable market conditions can support their resolution.

Third, similar patterns of divergence emerge when considering planned growth, visible in the evolution of subnational targets. India’s national solar targets have been revised upward on two major occasions. First in 2015, following a change in government, and again in 2021 under the same leadership. The initial goal, set in 2010, aimed for 20 GW of installed capacity by 2022, requiring annual additions of about 1.6 GW. In 2015, this was increased to 60 GW of utility-scale solar by 2022, raising the required annual rate to 7.6 GW. The most recent revision in 2021 set a target of 300 GW by 2030, with an estimated 180 GW expected from utility-scale projects, implying annual additions of 15 GW. At the state level, interim targets

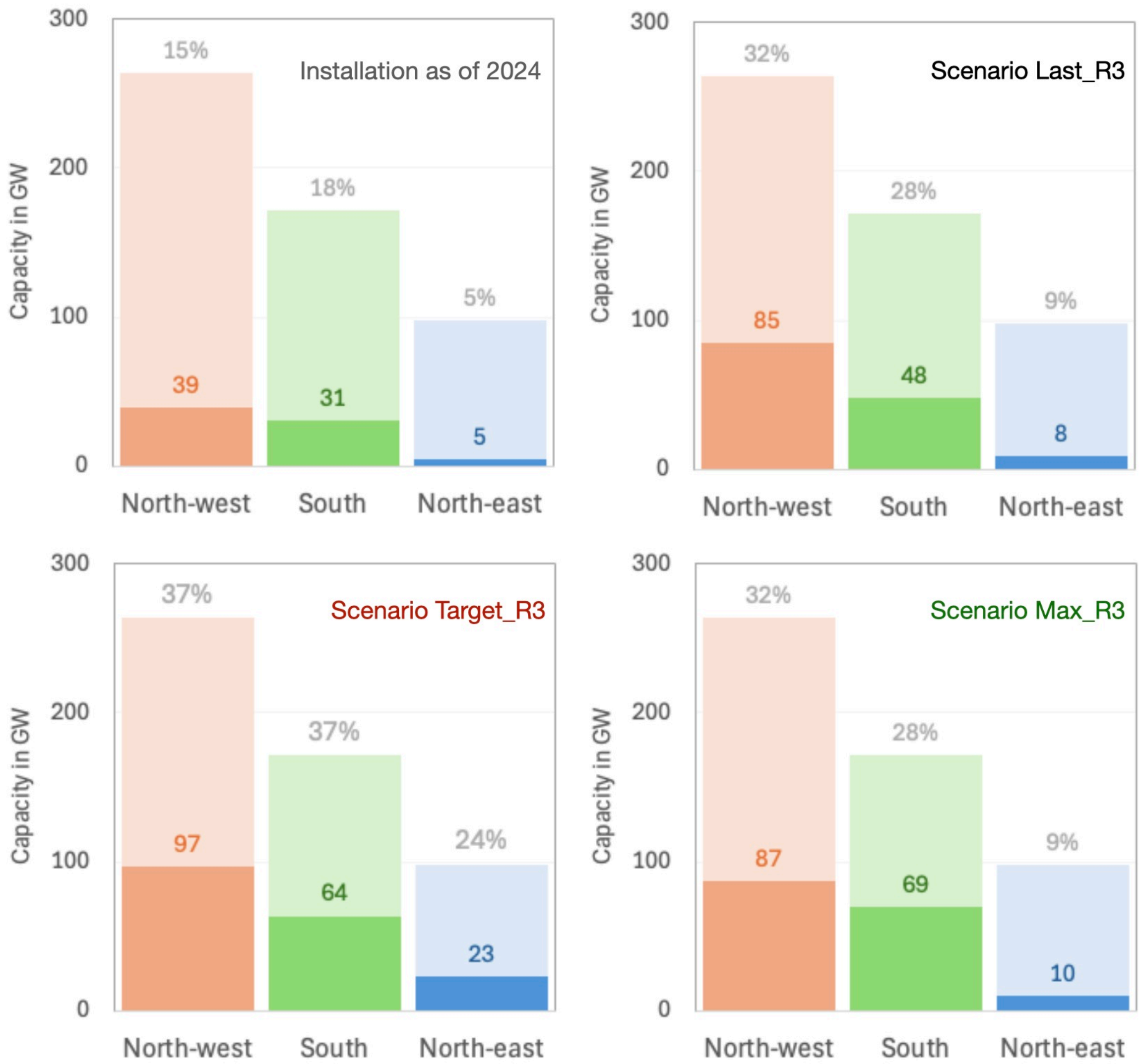

Figure 7.2: Actual deployment across regions as of 2024, versus projected 2030 deployment under different scenarios, relative to solar potential.

Solid numbers indicate absolute capacity, while grey values show the percentage of potential fulfilled.

have been announced by several governments, though not always with consistent upward revisions. See figure 6.5. States with historically low solar deployment, such as Punjab, Haryana, Uttarakhand, Bihar, and Odisha, have largely stagnated or scaled back their ambitions. Even previously high-performing states like Karnataka have shown reduced momentum. Both the upward revision of targets and tangible progress toward them remain concentrated in southern and northwestern states, regions with strong solar potential and a track record of early deployment. In contrast, northeastern states continue to exhibit both low ambition and low uptake, thereby reinforcing a long-standing pattern of spatial divergence. That said, an alignment between national and state-level targets was maintained throughout.

Building on methods outlined in, I further explored the conditions under which the 2030 solar targets might be achieved (see Figure 7.3). Under Scenario_R3latest, which extrapolates post-2021 growth trends, total solar deployment reaches only 141 GW by 2030 (47% of the 2030 target). Regional shortfalls are uneven — the north-west and south lag moderately, while the north-east significantly underperforms, reflecting a persistent divergence where leading regions consolidate their dominance and lagging regions continue to trail. Scenario_R3max, based on peak historical growth rates, offers a more optimistic but still unequal outlook. Deployment rises to 166 GW (55% of the 2030 target). The south slightly exceeds its goal, the north-west remains marginally below, and the north-east again falls far behind. Here, the structural rigidity of India's solar deployment landscape shows. Even under historically favourable conditions, convergence does not emerge organically. Only Scenario_Target, which assumes full realisation of the 180 GW utility-scale goal, suggests the possibility of regional convergence between the south and north-west, with each region achieving (approx.) 37% of its solar potential. While the northeast would contribute 24% of its potential. Yet this scenario reflects not a natural outcome, but a policy-driven path requiring extraordinary coordination and sustained effort across all 18 key states, requiring continued acceleration in the north-west, a return to peak growth in the south, and, most critically, a dramatic scale-up in the north-east. In other words, my findings reveal that convergence is not a guaranteed by-product of national ambition. Rather, it must be actively constructed through targeted, redistributive interventions. Without such deliberate policy effort, continued spatial divergence remains the default trajectory.

Taken together, my findings point to two main insights. First, solar uptake in India reflects a degree of coordination between national and state governments, with the national government playing an orchestrating role. Second, when viewed through the lens of cost-policy-technology co-evolution, policy efforts around utility-scale solar have reinforced, rather than reduced, spatial divergence. The assumption that cost declines and technology diffusion will naturally enable lagging regions to catch up is not borne out in the context. Instead, spatial divergence in utility-scale solar deployment appears entrenched, across historical trends, present dynamics, and future projections.

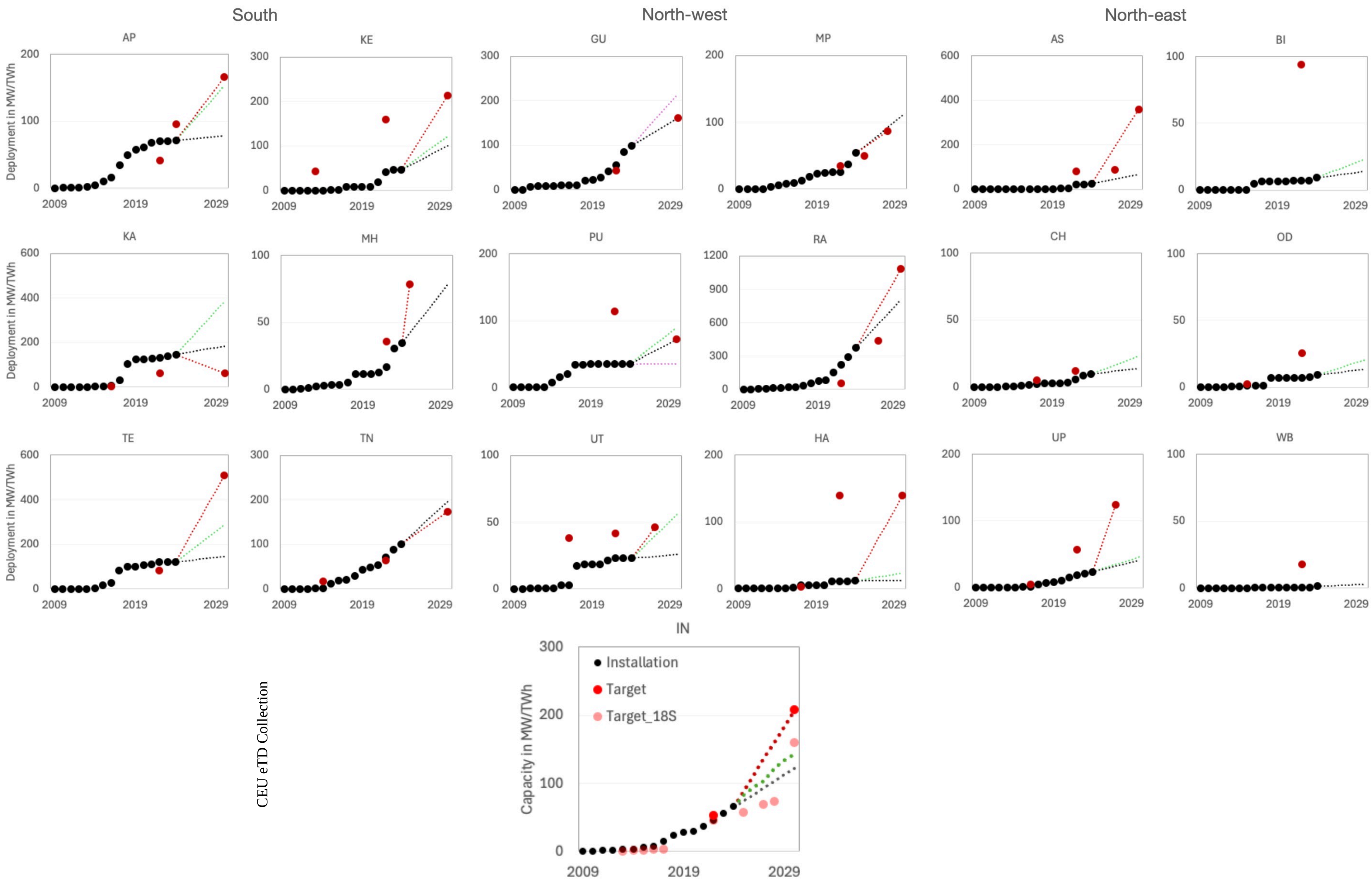

Figure 7.3: State-wise deployment paths to 2030 under three scenarios.

Black dots indicate actual deployment, and red dots indicate targets. Growth scenarios are based on linear fits: green shows $Scenario_MaxR3, blackshowsScenario_LastR3, andredshowsScenario_Target.$

7.4 Limitations and scope for future research

The contributions of this dissertation should be interpreted in light of a few important limitations, which also present opportunities for future research. These limitations stem primarily from the empirical scope of my study and the methodological choices underlying the analysis. Both of these may influence how broadly the conclusions can be applied. In this section, I reflect on how each of the four research questions has been addressed, identify key limitations associated with them, and highlight potential directions for future research.

The first objective of my study was to examine the relative influence of cost decline and policy effort in accelerating RE technologies over time. Drawing on India's solar experience, I showed that growth in deployment has been, and continues to be, primarily policy-driven. Once costs declined and reached parity points, growth did not proceed automatically. Rather, policy continued to play a crucial role in removing barriers (or market failures) and sustaining acceleration. I quantified this policy effort through the density and diversity of the active policy mix. Two key limitations emerge here. One, the analysis is based on a single-country case study. While comparable findings from a study of onshore wind in Germany (**?**), using similar methods, suggest this evolution of policy effort may not be unique to India, questions on generalisability remain open. Future research could extend this approach to other national and subnational contexts, as well as to different RE technologies at varying stages of technological maturity, to confirm the validity of claims. Second, while I conceptualise policy effort through a conceptually abstract framework that captures the intensity and scope of policy activity, I do not comprehensively quantify this effort in monetary terms. This quantification may have higher relevance for policymakers to allocate public spending or anticipate required financial support. Although there are indicative references, such as auctioned capacity volumes, contracting prices, and comparisons with alternative energy sources, a more systematic quantification of policy effort, perhaps even relative to GDP, might be valuable. The evolution of the financial scale of policy effort then, could more robustly be assessed compared to techno-economic cost improvements.

A third concurrent limitation of my study is that the true cost of solar electricity generation remains unknown. In Chapter 5, I show that standard techno-economic metrics, such as the LCOE, do not systematically capture the political and socio-technical costs associated with solar deployment. These include expenses and trade-offs related to land acquisition, grid integration, and political negotiations, all of which are central to assessing real-world feasibility and the broader effort required to scale RE technologies. Furthermore, the profitability of solar developers remains opaque. Such financial information is often embedded within private-sector decision-making processes, may be unevenly distributed among various social actors, and raises uncertainty surrounding policy support received on a project basis. While I identify these analytical gaps, in this dissertation, I do not empirically investigate them. A promising direction for future research could involve developing publicly accessible databases that track public expenditures on RE, similar to initiatives such as the International Institute for Sustainable Development's (IISD) tracking since 2014 (IISD 2024). A potential advancement would be to improve these databases by differentiating expenditures across RE technologies and deployment barriers. In this regard, barriers (or policy priorities) identified in this dissertation could offer a starting point.

Fourth, in addressing the second research question, I examined how policy efforts evolved in tandem with solar deployment by mapping the co-evolution of costs, technological growth, policy activity, and political change. This included analysing the timing, types, and density of policy responses, and offering insights into why particular policy actions emerged at specific stages of growth. While I implicitly explored and identified different feedback loops behind these dynamics, I did not systematically map them along the different stages of growth, which could be a potential avenue for future research. A more explicit and structured account of how both positive and negative feedback mechanisms emerge and evolve would offer a clearer understanding of the mutual interactions between technology development, cost trajectories, and policy responses. This is particularly relevant in later phases of technological diffusion, when barriers become more pronounced. Gathering enough evidence to characterise these feedbacks along distinct growth phases could be a potential first step towards operationalising and ultimately using them to enhance the accuracy and policy relevance of energy models popular at the science-policy interface.

Fifth, in addressing the third research question, I explored the timing and scope of barrier emergence for solar in India, compared with onshore wind in Germany. The idea was to contrast a technology-recipient country with a technology-pioneering one, both featuring somewhat mature RE technologies. My findings challenged the optimistic notion that developing countries can "leapfrog" fossil-based energy systems by easily adopting cheaper renewable technologies without similar levels of policy effort. While I do not directly assess whether technological leapfrogging has occurred, or the extent to which economic gains in recipient countries can be attributed to technology transfer from frontrunners versus domestic policy efforts, these remain important areas for further research. Additionally, examining the generalisability of emerging barriers in similar contexts could help clarify the extent to which policy intervention is still required in technology recipients, and what aspects of the transition, if any, can be effectively driven by cost decline and market forces alone.

Finally, in addressing the last research question from a subnational perspective, I acknowledge that the future trajectory may diverge from past patterns, especially within a dynamic market context where the technology is still rapidly maturing and evolving. Nonetheless, I find that although solar deployment in India has expanded across both early- and late-adopting states, there is little evidence of convergence. National targets, expressed in absolute terms, have reinforced regional divergence, even though these targets appear equitably distributed on paper, particularly when aligned with states' solar potential. Moreover, actual policy implementation, evolving alongside cost trends, seems to entrench pre-existing regional disparities. Over time, resources and support have increasingly concentrated in states with higher solar potential. This skewed evolution raises critical concerns about whether current deployment strategies can effectively balance the dual objectives of accelerating renewable growth and promoting equitable regional development. It remains an open question whether these patterns are unique to India or reflect broader trends. Future research could investigate how policy efforts are spatially differentiated based on resource potential, and whether deliberate strategies exist to support lagging regions or if resource allocation is primarily optimised for high-performing areas.

8. Conclusion and summary

This dissertation explored the relative role of market advantage and policy effort in accelerating the growth of a renewable energy (RE) technology over time and space. In Chapter 1, I introduced the rationale for the research, framed around two central puzzles, and outlined the objective of addressing four research questions. Chapter 2 reviewed the literature and explored the disciplinary origins of these puzzles. Here, I situated the four research questions against the knowledge gaps they address. In Chapter 3, I developed the conceptual and analytical framework of the research. Chapters 4, 5, and 6 formed the analytical core of the dissertation. In Chapter 7, I synthesised my main contributions, acknowledging the limitations, and outlined directions for future work. In this final chapter, I offer a zoomed-out summary, situating my findings within the wider policy context.

The two sides of an open debate.

The science is unequivocal that mitigating climate change demands a fundamental transformation in how we produce and consume energy. Most leading studies outlining viable pathways to deep decarbonisation converge on three medium and long-term imperatives (IEA 2021b; IPCC 2023): a rapid expansion of the electricity sector; a sustained and accelerated deployment of renewable energy (RE) technologies, especially solar; a concentration of this growth within emerging economies, such as India. The challenge, however, lies in the complex interplay between the urgency of this transformation, the uneven global capacity to achieve it, and the insufficiency of current progress. First, while historical energy transitions have unfolded over decades, the low-carbon transition must occur much faster (Grubler et al. 2016; Kramer and Haigh 2009; Sovacool and Geels 2016). Second, integrating renewables into electricity generation is not merely a matter of fuel substitution but requires a fundamental overhaul of systems designed around qualitatively and operationally different energy sources (Christophers 2024; Köhler et al. 2019). Third, although emerging economies offer significant opportunities, such as abundant solar potential, rising energy demand, and the chance to leapfrog long arcs of R&D and early policy learning, they also face steep structural barriers (Hansen et al. 2018). These include high investment risks (Ameli et al. 2021), weak institutions (Zanello et al. 2016), and infrastructural deficits (Cantarero 2020) that hinder a smooth technology transfer. Finally, despite the accelerating growth of solar, its current pace remains well below what is needed to meet global climate targets (Jakhmola et al. 2025; Suzuki et al. 2023; Vinichenko et al. 2023).

These tensions raise a key question that lies at the heart of this dissertation. What will actually get us where we need to go? More specifically, what should be the role of policymakers in driving the grand transition, and how much can be entrusted to market forces alone? One view holds that, once technology costs fall, market forces will largely drive solar adoption. The other argues that ongoing policy support remains essential, even after costs decline. The disagreement rests on both temporal and spatial dimensions. Temporally, the market-driven view accepts that early policy support is necessary to reduce technology costs but expects markets to take over once solar becomes cost-competitive (Creutzig et al. 2017; Liñeiro and Müsgens 2025; Victoria et al. 2021). The policy-driven view counters that cost competitiveness alone does not eliminate barriers, such as grid integration, land acquisition, and resistance from incumbents, thereby requiring sustained policy effort throughout (Breetz et al. 2018; Frantál et al. 2023; Ollier et al. 2024). Spatially, the market-driven view suggests that technology-recipient countries can benefit from the experiences of pioneers and leapfrog traditional development pathways with relatively less policy effort (Arndt et al. 2019; Bogdanov et al. 2021; Gulagi et al. 2022). In contrast, the policy-driven view contends that early-stage challenges often persist and inhibit eventual uptake, demanding greater and more sustained policy engagement in these contexts (Gallagher 2006; Mazzucato 2016; Yap et al. 2022).

The methodological distance between the two sides.

In Chapter 2, I show that the debates reflect deep-seated disciplinary divides. This manifests as a mismatch between the types of knowledge each discipline produces and the extent to which they are integrated into tools popularly used to inform decision-making at the science-policy interface. The market-driven perspective is largely rooted in environmental and energy economics, which prioritises macro-level, quantitative insights and generalisability (Beek et al. 2020). This body of work underpins the development of Integrated Assessment Models (IAMs), which have grown in prominence due to rising policymakers' demand for data-driven forecasts, advances in modelling capabilities, and proactive engagement by the modelling community (Beek et al. 2020). Yet, IAMs are often criticised for their narrow focus on techno-economic cost optimisation, overlooking the socio-political complexities that influence cost-policy-technology co-evolution (Geels et al. 2016; Jewell and Cherp 2023; Trutnevyte et al. 2019).

In contrast, the policy-driven view is informed by political science, energy geographers, innovation studies, and newer economic traditions. Scholars in these fields argue that energy transitions are embedded in socio-political contexts and cannot be fully captured through economic modelling alone. They challenge the foundational assumptions of IAMs, contending that such models fail to reflect the messiness of real-world transitions. Alternative frameworks from these fields foreground institutional, political, and social dynamics, highlighting feedback loops - both reinforcing and constraining - that shape the co-evolution of technologies and policies (Ayoub and Geels 2024; Edmondson et al. 2020; Sovacool et al. 2025). Some researchers have also examined the effectiveness of specific policy interventions or broader features of policy mixes - such as their stringency, sequencing, diversity, and density - and their links to technology growth (Li et al. 2025; Nachtigall et al. 2022; Pahle et al. 2018; Schaub et al. 2022; Sewerin et al. 2023). However, these studies do not always measure policy effort holistically, and their strong emphasis on context specificity limits the generalisability of their findings for anticipating future pathways. Furthermore, most studies here are based on developed-country contexts, overlooking the distinct challenges that technology recipients face, despite the latter's central role in future solar deployment.

A modest step towards arbitrating between the two sides.

In this dissertation, I make a modest contribution toward bridging these divides. I do so by contextualising generic variables, such as LCOE and grid parity, which are commonly used in the first (techno-economic) approach, and rendering them their missing contextual specificity. Next, I quantify contextual variables, such as density and diversity of policy actions used in the second (socio-technical and political) approach, rendering them a more holistic and generalisable picture. Finally, I demonstrate how integrating these knowledge types reveals what it takes to accelerate renewable energy in a developing country context. To achieve this, I developed an analytical framework based on Cherp et al. (2018) that integrates techno-economic, socio-technical, and political perspectives of energy transitions. I operationalised the framework in a novel semi-quantitative way, tailored to India's utility-scale solar context. Here, I capture the market- and policy-driven views through a structured, four-step approach.

First, within the techno-economic perspective (Chapter 5), I examined how solar electricity costs evolved and became competitive. I distinguished between absolute costs (measured by the levelised cost of electricity, LCOE) and relative costs (LCOE compared against four electricity price benchmarks). In doing so, I adapted and extended the concept of grid parity to make it temporally and spatially dynamic and actor-specific. This allowed me to capture cost trends and test the market-driven view. Second, within the political perspective (Chapter 6), I analysed the evolution of policy effort using the conceptualisation by Lieberman and Ross (2024). I mapped political ambitions to 2030 and assessed the density and diversity of policy actions through an original classification scheme. This revealed how shifting policy priorities corresponded to emerging barriers at different stages of solar growth, and how national and subnational governments acted as agents of targeted interventions. This perspective captured policy trends and tested the policy-driven view.

Third, through the socio-technical perspective (Chapters 4, 5, and 6), I examined how social actors' behaviours and technological growth co-evolved over time and space. This perspective showed how cost and policy trends both shaped and were shaped by actors such as state-owned DISCOMs and central off-takers conducting auctions, and private developers installing capacity. Finally, to establish causal relationships, I used process tracing grounded in a mechanistic understanding of social change (Mahoney 2012). I combined prospective tracing (to test theory-informed hypotheses) and retrospective tracing (to explain surprising outcomes), constructed time-series visualisations to track sequences of change across cost, policy, and technology, and employed counterfactual reasoning to test causal claims across states and time periods.

In sum, I examined the co-evolution of cost, policy, and technology over time (2004–2024) and across space (18 states encompassing nearly all of India's utility-scale solar capacity), offering an integrated, multi-scalar, and time-series view. I preserved the importance of contexts, framed the two viewpoints in a way that aligns with existing literature, and put forward an analytical approach that allows yielding somewhat generalisable insights. Then I demonstrated the use of the tool capable of testing claims for similar technologies. I answer four research questions. Two are on the temporal dimension, and two are on the spatial dimension of the debates involving the relative role of costs and policies in accelerating RE technology growth.

1. What is the relative role of market advantage and policy effort in accelerating solar growth over time?

2. How do policies change over time as solar deployment increases?

3. What is the relative role of policies in accelerating solar growth in a technology-recipient

country?

4. How do policies change over space with increasing solar deployment, sub-nationally? Do they enable late adopters to catch up?

Despite strong market advantage, utility-scale solar in India has and continues to be primarily policy-driven.

My findings show that utility-scale solar in India has been, and continues to be, primarily policy-driven. While India benefits from substantial solar resources, growing electricity demand, and significant declines in solar generation costs, these market advantages alone have not sustained deployment. Over the last decade, solar consistently became more cost-competitive (Figures 5.4 and 5.6). In 2017, auction tariffs reached price-parity, where contracting new solar became cheaper than the national wholesale electricity price. By 2021, solar had reached both cost-parity (where building new solar was cheaper than buying electricity from the grid) and cross-source-parity (where contracting new solar became cheaper than coal-based electricity for state DISCOMs, even accounting for legacy contracts). These milestones are often interpreted in the literature as positive tipping points for market-led growth. Yet, in India, solar deployment trends diverged from these expectations. After price-parity, installations briefly accelerated but slowed within a year. Following cost parity and parity with coal, deployment merely stabilised at the national level, rather than accelerating at (similar) rates seen during the pre-slowdown phase. Subnational patterns reinforced this disconnect. Deployment increased in northwestern states despite not achieving parity with coal, declined in southern states even after achieving parity with coal, and had little impact in the north-east despite reaching parity with coal.

Instead, consistent and evolving policy support has been crucial, as evidenced by the expansion of a proactive and diverse policy mix (Figures 6.6 and 6.7). My finding, therefore, supports the policy-driven view that policymakers promoting renewables like solar PV cannot withdraw after addressing a single market failure - namely, high generation costs - but must continuously tackle emerging socio-technical and political barriers. In other words, rather than unlocking self-sustaining momentum after reaching cost-competitiveness, solar in India repeatedly encountered recurring market failures that policies helped overcome to maintain national acceleration. This was reflected in social actors' responses. Private developers, more sensitive to market signals, followed the trends described above. At the state level, publicly owned DISCOMs responded differently. Early adopters slowed procurement post U-parity, while states like Gujarat, Maharashtra, and Rajasthan - previously less active - scaled up auction activity (Figure 5.9. In contrast, national public-owned entities like SECI and NTPC responded more systematically (See also Figure 5.8 for NTPC activity). They significantly ramped up auction activity after parity incidences. This response was driven by the need to stabilise deployment amid weakening institutional capacity, sub-nationally, and investor retreat from growing market uncertainty. In other words, engagement by national off-takers was shaped more by political intent than by pure market logic.

Cost decline, policy effort, and technology growth co-evolve over time.

As solar deployment increased, the policy landscape became not only more expansive and diverse but also increasingly complex. Policies enabled but were also shaped by solar growth. Interventions responded to technology-specific barriers, such as the need for market creation, system integration, complementary technologies and infrastructure, domestic manufacturing, and land use and acceptance. These barriers are not unique to India. See (**?**). Yet, policies were also shaped by external shocks (e.g., COVID-19 crisis, international trade tensions) and political developments (e.g., regime change and the emergence of political entrepreneurs). Both reflected contingent, yet not uncommon, aspects of energy transitions. See Table 6.3. In their evolution, policies did not align neatly with the technology's lifecycle. Older interventions persisted even after new challenges emerged. Policy efforts also varied across governance levels. National-level policies were broader and more diverse, while state-level interventions focused more narrowly on implementation challenges such as land acquisition and system integration (Table 6.2 and Figure 6.8). Yet, national policy momentum often aligned with visible pulses in solar growth (Figure 6.9). Here, policies both enabled and constrained solar growth. For instance, a surge in installations coincided with the 2021 expansion of system integration and complementary technology policies, whereas the uptick of domestic manufacturing policies in 2018 contributed to a national slowdown.

These non-linear patterns reflected the co-evolution of cost trends, policy efforts, and technology growth. For example, early-mover DISCOMs in southern India (central to driving down solar tariffs through aggressive auction-based procurement until 2017) became locked into high-cost PPAs. Facing mounting financial strain, they withdrew from new auctions, slowing regional growth. National entities like SECI and NTPC were then compelled to step in to stabilise procurement. See Figure 5.9. Among private actors, cost declines enabled market consolidation. Large developers expanded their share, while smaller firms exited under financial pressure (Figure 5.7). This shifting actor configuration allowed dominant firms to exert increasing influence on new policy adoption. The 2018 import tariff was one such outcome. Developers with manufacturing capacity - most notably Adani - lobbied for protectionist measures that benefitted their vertically integrated model, while others opposed them. This intra-industry contestation undermined the notion of a unified niche coalition. In the context of a predominantly privately owned sector, internal politics within the niche industry diverged from the shared objective of accelerating RE deployment. Policies helped overcome the situation.

That said, while cost decline did not substitute for sustained policy effort, it expanded the policy space by enabling more ambitious and politically contentious interventions. The 2018 import tax, despite resistance from developers, was ultimately enforced after solar had already reached price parity. After this point, while auction tariffs stabilised due to rising costs, solar's competitiveness with the average wholesale electricity price was maintained. This, combined with a 2017 initiative offering developers credible off-takers and predictable demand, helped avert what many anticipated would be a prolonged slowdown of technology growth. The continued appeal of solar to public procurers highlights two reinforcing dynamics. First, that cost-competitiveness preserved market momentum in the face of backlash and regulatory shifts. Second, declining costs rendered new interventions economically and politically viable. India's broader energy transition patterns reflect this logic. For example, steep cost declines preceded key policy measures. For example, the upward revision of the 2022 target in 2015 preceded sharply declining costs and auction tariffs. The 2021 announcement of the 2030 RE goals followed achievement of cost- and coal-parity, along with major post-2021 policy adoptions, including the high cost coal phase-down agenda and the introduction of a national carbon trading scheme. While some of these policies align with global developments, such as the 2015 Paris Agreement or the forthcoming introduction of EU's CBAM, they are rooted in strong domestic confidence surrounding solar's techno-economic progress. In sum, my findings here expanded existing accounts of technology–policy co-evolution and highlighted additional feedbacks between cost decline, policy change, and technology growth.

The sequencing of barriers for accelerating solar in India reflected higher policy effort.

While barriers to solar uptake are broadly shared across contexts and other RE technologies, their sequencing differs significantly between pioneering and recipient countries. This difference has important implications for the scale and intensity of policy effort required in the latter context. My findings on utility-scale solar in India reveal that the difference in the timing of system integration, grid expansion, and industrial policies has amplified both the intensity and persistence of policy effort needed to drive acceleration. In other words, they highlight the limitations of relying solely on declining global technology costs and challenge the assumption of a straightforward, easy leapfrogging pathway. In India, system integration and grid expansion policies, such as curtailment protection, regulations on electricity trade, and expansion of transmission and balancing infrastructures, had to be introduced at early stages of technology growth. In simple words, India had to front-load its integration efforts due to the absence of the foundational grid and market infrastructure necessary for incorporating new energy sources, let alone one that is so qualitatively different.

By contrast, industrial policies towards domestic manufacturing followed a different trajectory. Although local content requirements were embedded in solar auctions from an early stage, substantive support towards the manufacturing sector only scaled up after 2018 - four years into solar acceleration and eight years after national solar policy adoption. This delay reflected a strategic policy choice that policymakers in technology-recipient countries face: whether to prioritise technology deployment and rapid capacity growth, or domestic supply chain development during the formative phase. In the Indian solar case, policymakers chose the former. Yet, manufacturing considerations did not disappear. Instead, they resurfaced more forcefully at later stages of solar growth, creating tensions that contradicted the acceleration rationale and required mediation through additional policy effort. Importantly, the intensity of this effort cannot be attributed to sequencing alone. For instance, China's success in establishing a robust PV supply chain was not simply a matter of timing but of sustained, large-scale policy experimentation and long-term commitment to manufacturing as a strategic objective at the formative stage.

In India, policies accelerating solar growth led to persistent spatial divergence in technology diffusion sub-nationally.

Despite nationally coordinated efforts, past and planned patterns of utility-scale solar expansion in India suggest persistence of spatial divergence. To begin, no relation was found between policy density and solar deployment across Indian states. A moderate positive correlation emerged when considering policies specifically targeting land acquisition and system integration, though the direction of causality remains untested and thus unclear (Section 6.2.2). In contrast, a regionally distinct technology growth pattern evolved as a result of national-level policy interventions over time. Early-adopting states in the north-west and south drove much of the initial growth, while states in the north-east have remained largely absent from this expansion. At first, growth was led by the north-west (until 2013), then the south (2014-2018), and then by the north-west again (2021 onwards). Each episode reflected the involvement of the current national government or the adjacent implementation agencies.

At times, the involvement was explicit. For example, early acceleration led by the north-western and southern states involved early support for Karnataka, Andhra Pradesh, Gujarat, and Rajasthan. See Figure 6.10. Other times, the effect of national policy action was implicit. For example, when import duties and global supply disruptions increased the cost of solar generation post-2018, credible national off-takers providing consistent demand helped mitigate development risk. These auctions, though open to all states, disproportionately attracted investments to resource-rich regions in the north-west (away from financially burdened DISCOMs in the south), reinforcing rather than correcting regional disparities (Figures 4.1). As a result, national policy choices aimed at maximising speed and efficiency disproportionately favoured high-potential geographies, while deferring engagement with lower-return regions, with more complex barriers. This is not to suggest that the leading regions were free from barriers. Rather, stronger market advantages in them allowed absorbing and navigating challenges more effectively.

Against the backdrop of a nationally coordinated effort to accelerate solar and meet ambitious targets, policies designed to unlock positive feedback loops in technology growth did so at the expense of ensuring equitable diffusion. This raises questions about one, the compatibility of equitable development with accelerated RE deployment, and two, the scale of policy effort ensuring such equity would require. Scenario explorations suggested that under business-as-usual conditions, India is unlikely to meet its 2030 utility-scale solar targets, with shortfalls heavily concentrated in the north-east, thereby prolonging existing regional disparities. Even in optimistic scenarios, early leaders are projected to maintain their dominance, while lagging states continue to fall behind. Spatial convergence, measured against each region's solar potential, when targets are fully achieved, only materialises for the north-west and southern states. However, this is neither a natural consequence of falling costs nor of learning spillovers from early adopters. It would demand deliberate, sustained, and escalated policy efforts: the north-west would need to maintain its current momentum; the south would have to regain its peak historical growth rates. For the north-eastern states to meet their targets, they would need to grow at an unprecedented pace. See Figures 7.2 and 7.3.

Limitations and potential for future work

There are three main limitations of this dissertation, each offering avenues for future research. The first concerns the generalisability and scope of the findings. While I provide in-depth insights into the dynamics of solar expansion in India, conclusions regarding the relative roles of costs and policies in driving RE acceleration across time and space are drawn from a single-country case study. This inevitably raises questions about the broader applicability of the findings. Although temporal patterns of emerging barriers resonate with other contexts (e.g., onshore wind in Germany), further research is needed to assess the general validity of these claims. Future studies could extend this analysis to other national and subnational settings, through comparative cases across different stages of technology growth. Of particular value would be a greater understanding of the sequencing of barriers across both time and space. Temporally, it would be important to document how positive and negative feedback in technology-policy co-evolution align with distinct phases of growth. Such documentation could serve as a foundational step toward integrating these dynamics into more realistic energy models. Spatially, further investigation is needed into how barriers emerge in technology-recipient regions, those expected to host the bulk of future RE deployment. Examining whether the barriers identified in India generalise to such contexts would help clarify the degree to which policy intervention remains necessary, and what aspects of the transition, if any, can be effectively driven by cost decline and market forces alone.

The second limitation relates to the lack of precise knowledge about the true cost and policy effort required to accelerate solar, and, more broadly, RE technologies in a developing country context. My findings demonstrate that common techno-economic cost metrics fail to capture the full spectrum of costs associated with solar deployment, including institutional, infrastructural, and coordination-related challenges. This has important implications for understanding the relative contributions of policy and market forces in driving acceleration. Moreover, developers' actual profit margins remained opaque, further complicating assessments of risks and market efficiency. That said, my findings show that, despite substantial declines in technology costs, accelerating solar would not have been possible without sustained policy support. Yet, the full intensity of this effort, particularly in financial terms, remains unknown. Identifying the magnitude of this effort and understanding who ultimately bears these costs could offer more operational insights into the policy needs of accelerating RE transitions, beyond simply acknowledging the presence of enabling policy instruments.

Finally, my findings on spatial divergence suggest that policy efforts have tended to reinforce regional inequalities rather than reduce them. Future research should examine whether this pattern is unique to India or indicative of broader tendencies in renewable energy systems. In particular, it would be important to understand how policies can be effectively tailored to support lagging regions, and whether accelerating RE transitions is compatible with equitable transitions, and if so, what would it take.

Policy recommendations

In 1959, Charles Lindblom famously observed that policymaking is rarely a linear, technocratic exercise. It unfolds incrementally, through a process of "muddling through" amid uncertainty of results, limited resources, and often competing and changing priorities of policymakers. This, coupled with the urgency of mitigating climate change, makes it important to equip decision-makers with realistic insights into what accelerating RE technologies demand in practice. My recommendations speak directly to these conditions. Drawing on India's experience with utility-scale solar, I offer three core insights on: (i) the scale of policy effort, (ii) knowledge on sequencing and feedbacks that drove RE acceleration in a technology-recipient country, and (iii) the need to make visible the full costs of policies.

First, it is important to acknowledge the scale of effort required to accelerate RE technologies, like solar PV. In India, utility-scale solar growth has remained largely policy-driven, despite its apparent market advantage and cost competitiveness. Deployment plateaued, slowed, or remained unchanged on multiple occasions, even after reaching cost parity points. This is because new and evolving barriers emerged as a reflection of the deep socio-technical and political transformations that RE transitions demand, and which policymakers must navigate. Additionally, late adopters, whether at the national or subnational level, could not rely solely on technology or policy learning from early adopters[54]. In both contexts, either greater upfront effort was required (at the national level, to integrate solar through system integration and complementary technology and infrastructure policies) or will be required (at the subnational level, particularly in the north-east, to meet targets and accelerate growth). That said, while cost-competitiveness alone did not guarantee acceleration nor eliminate the need for policy intervention, it created space for more ambitious, and sometimes contentious, policy decisions while maintaining growth. Given these complexities, it is essential to scrutinise the underlying assumptions in energy models that optimise for technology cost reductions before using them to guide policymaking.

Second, navigating RE transitions requires a clear understanding of when and how key barriers emerged during the deployment process, particularly in a technology-recipient developing country. India's experience provides insight into anticipating and managing the feedbacks be-

[54]At the national level, I have referred to them as technology-recipient and technology-pioneering countries respectively.

tween technology and policy, from a successful case. Technology-specific barriers included challenges related to market creation, domestic manufacturing, system integration, complementary technologies and infrastructure, and land use and acceptance. Figures 6.6 and 6.8 showed at what stage of technology deployment these barriers rose and what tools were used to address them, across governance levels. Table 6.3 examined the role politics and external shocks played in shaping outcomes. Section 6.3 documented the various positive and negative feedback loops that arose as a result of these interventions, offering insight into how the sequencing of policies contributed to, or constrained, technology growth over time and across space. To support this learning, I developed visualisations that map these interrelated policy, technology, and cost dynamics. The tool might not only help speed up policy learning in similar contexts but also support cross-country insights and comparisons.

Finally, I recommend better tracking and visibility of public expenditure to understand the real cost of accelerating RE technologies in both similar and across contexts. One of the major constraints in this research was the absence of consistent, transparent data on public expenditure related to solar deployment — across instruments, levels of government, and time. This made it difficult to quantify the actual effort behind policy interventions or to assess their intensity relative to technology cost decline. Yet this knowledge is critical. Understanding what it financially takes to overcome socio-technical and political barriers that persist, especially after technology cost declines, would be essential not only for national planning and more viable pathways but also for informing transitions elsewhere and seeking financing. Establishing and maintaining databases that document renewable energy spending in granular detail — by barrier type/policy goal, and governance level could enhance scenario modelling accuracy, support evidence-based policy learning, and improve planning. For countries like India, expected to play a central role in global decarbonisation, this is not just a technical task. Rather, it might be a strategic investment in improving visibility of the required policy effort..

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A. Appendix

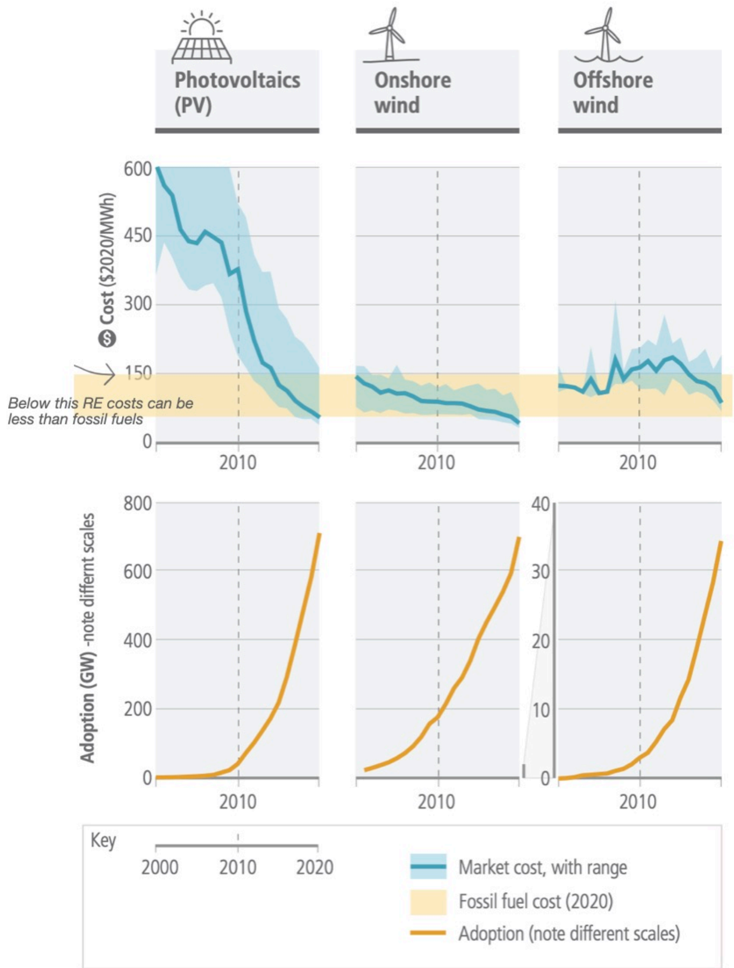

Figure A.1: Cost decline and the corresponding growth in RE technologies globally, between 2000-2020.

Source: IPCC (2023) p.54.

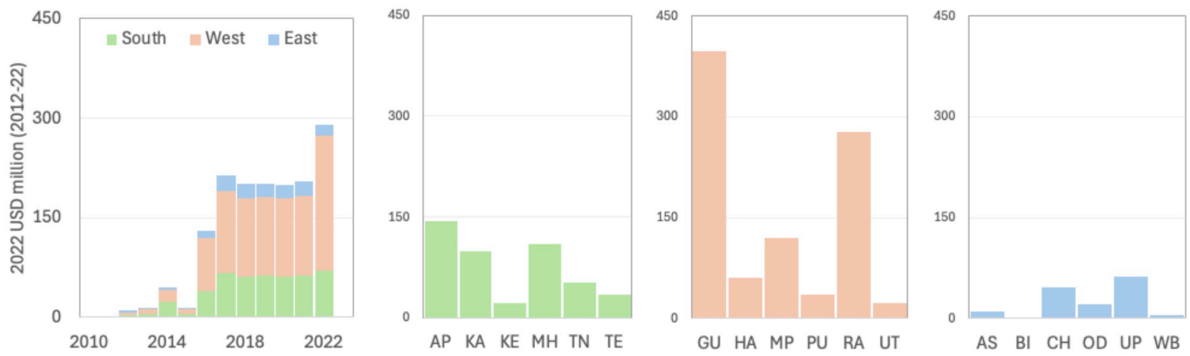

Figure A.2: Total national financial assistance allocated to states for promoting grid-connected solar in India.

Source: MNRE (2015a, 2023a,b).

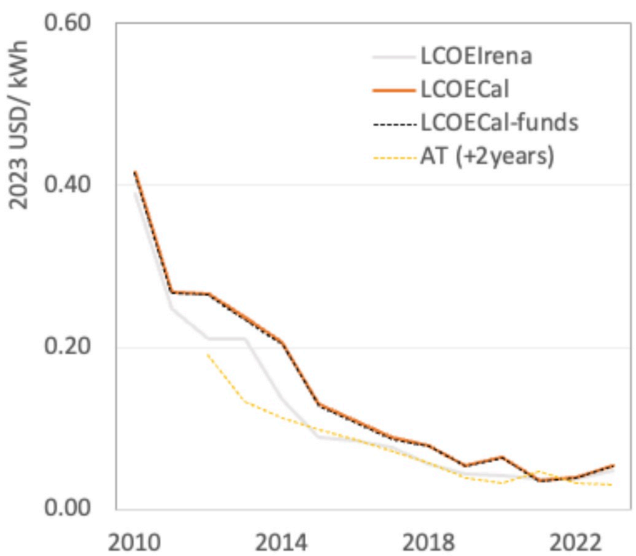

Figure A.3: Utility-scale solar LCOE in India after accounting for national financial assistance.

	IRENA assumptions or China in 2021 Based on IRENA 2023 generation cost report	Wang et al 2023 Their source of data extends from (2015-2021)
CAPEX without land, USD/kw	672	654
Land acquisition cost, USD/kw (1kw is assumed to require 20 sq. m. of land)	*in opex*	336.6 for cropland 618.2 for forest land 609.2 for built-up land 93.8 for barren land
CAPEX with land, USD/kw	672	748 - 1272
OPEX, USD/kW/year	9.6	7.4 - 12.6
Discount rate (in %)	2.5	5

Table A.1: Differing assumptions for solar LCOE in China between IRENA (2023) and by Wang et al. (2023).

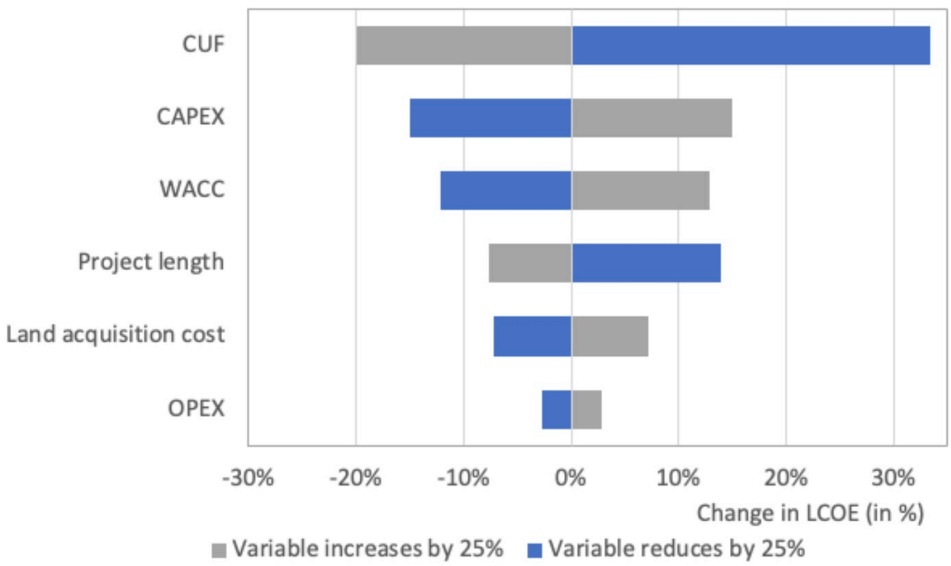

Figure A.4: Sensitivity analysis for utility-scale solar LCOE calculations.

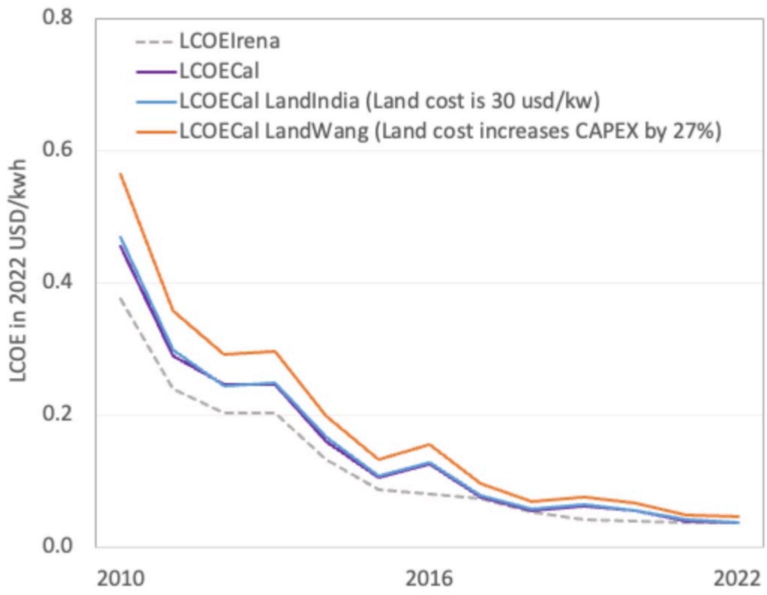

Figure A.5: Utility-scale solar LCOE in India under varying land cost assumptions.

Years	INR equivalent to 1 USD	Deflator
2010	45.56	0.74
2011	47.92	0.75
2012	54.41	0.76
2013	60.5	0.78
2014	61.14	0.79
2015	65.47	0.80
2016	67.07	0.81
2017	64.45	0.82
2018	69.92	0.84
2019	70.9	0.85
2020	72.37	0.86
2021	74.00	0.90
2022	82.48	0.97
2023	82.60	1

Figure A.6: Exchange rates and deflators used in this dissertation.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
AP								3.0	4.0	5.0	6.0	7.0									
AS						0.3	1.0	4.0	5.0	6.0	7.0	8.0									
BI							1.5	2.3	3.3	4.8	6.8	8.0									
CH	0.3	0.3	0.5	0.5	0.8	1.0	1.5	2.0	3.5	5.0	6.5										
GU	0.3	0.5	1.0	1.0	1.3	1.5	1.8	1.8	4.3	5.5		8.0	8.0	9.5	11.3						
HA							2.8	2.8	3.0	3.0	3.0	3.0									
KA						0.0	0.8	2.8	6.0	7.3	8.5	10.5		11.5	12.5	13.5	14.5	15.5	16.5	17.5	19.0
KE								0.5	1.5	2.8	4.0	5.3	6.8	10.5	10.5						
MP		0.4	0.6	0.8	1.0	1.0	1.3	1.5	1.8	4.0	6.0	6.0	8.0								
MH											4.5	6.0	8.0	10.5	13.5						
OD		0.1	0.2	0.2	0.3	0.5	1.5	3.0	4.5	5.5			7.3	8.0							
PU		0.0	0.1	0.1	0.2	1.0	1.3	1.8	2.2	4.0	5.0	6.5	8.0								
RA						1.5	2.0	2.5	4.8	4.8	6.0	7.3	8.5	9.5	10.5						
TN		0.5	0.5	0.5	0.5	0.5	0.5	2.5	5.0	5.0	8.0	10.5									
TE									5.3	5.8	6.2	7.1		7.5	8.0	9.0	10.0	11.0			
UP	0.3	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	3.0	4.0	5.0	5.0							
UT				0.1	0.8	0.1	0.3	0.5					10.5								
WB					0.1	0.2	0.2	0.3	0.3	0.4	0.4	3.0	4.5	6.0							

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
AP								0.09	0.11	0.13	0.15	0.17		0.18	0.19	0.20	0.22	0.24			
AS						0.07	0.04	0.09	0.11	0.13	0.15	0.17									
BI							0.07	0.08	0.09	0.12	0.14	0.17									
CH	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.11	0.13	0.15	0.11	0.12	0.13	0.27	0.30	0.33	0.36	0.39	0.41	0.43
GU	0.05	0.06	0.07	0.07	0.08	0.09	0.10	0.10	0.13	0.14		0.17	0.17	0.19	0.21						
HA							0.04	0.05	0.07	0.09	0.10	0.11									
KA						0.15	0.17	0.21	0.25	0.30	0.31	0.33		0.39	0.44	0.48	0.53	0.58	0.63	0.67	0.73
KE								0.05	0.08	0.10	0.12	0.14	0.17	0.21	0.22	0.40	0.43	0.46	0.48	0.49	0.50
MP	0.01	0.03	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01				0.25	0.27	0.29	0.31	0.33	0.35	0.36	0.38
MH											0.16	0.18	0.20	0.22	0.25	0.30	0.33	0.36	0.39	0.41	0.43
OD	0.05	0.05	0.06	0.06	0.07	0.03	0.05	0.08	0.10	0.11			0.13	0.15	0.27	0.30	0.33	0.36	0.39	0.41	0.43
PU		0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.10	0.12	0.15	0.18		0.27	0.30	0.33	0.36	0.39	0.41	0.43
RA			0.06	0.07	0.08	0.09	0.10	0.11	0.14	0.13	0.15	0.17	0.18	0.20	0.22	0.30	0.33	0.36	0.39	0.41	0.43
TN		0.09	0.09	0.09	0.09	0.09	0.10	0.12	0.14	0.14	0.18	0.21			0.27	0.30	0.33	0.36	0.39	0.41	0.43
TE									0.06	0.07	0.07	0.08		0.09	0.09	0.11	0.12	0.13			
UP	0.04	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.08	0.11	0.13	0.14	0.15							
UT				0.06	0.07	0.08	0.09	0.11					0.21	0.25	0.27	0.30	0.33	0.36	0.39	0.41	0.43
WB					0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.12	0.15	0.17							

Table A.2: State-wise solarRPO targets (top) and totalRPO targets (bottom) between 2010-2030.

Data collected from various policy documents.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Sources
AP													2500		6400	10120						Solar Policy 2015, Solar Policy 2019-2024, Hybrid policy 2018-2024, Export Policy 2020-2025
AS													398					432			1800	Solar policy 2024 - 2030
BI													1969									2011 Solar policy, 2017 Solar policy
CH								450					1070									2012 Solar policy
GU													4812								18000	2023 Solar Policy
HA								60					3200								3200	2014 Solar Policy, 2016 Solar Policy, 2023 solar policy
KA							200						3600					9000				2011-16 solar policy, 2014-21 Solar policy, RE policy 2022-27
KE				300									1122								1500	2013 Solar policy,
MP													3405			4845			8445			2022 Solar Policy
MH													4500			10000						2015 Solar Policy, 2020 Solar Policy
OD						135							1426									2013 Solar Policy, 2016 Solar Policy
PU													2863								1800	2012 Solar Policy, 2019 Solar Policy
RA													3457					26260			65000	2011 Solar Policy, 2014 Solar Policy, 2019 Solar Policy, 2019 Hybrid Policy, 2023 Solar Policy
TN					1500								5400								14760	2012 Solar Policy, 2019 Solar Policy
TE													2950								18360	2025 Clean and Green Energy Policy
UP							500						6418					14000				2013 solar policy, 2022 Solar policy
UT							500						540					600				2013 solar policy, 2022 Solar policy
WB													3202									-

Table A.3: State-wise utility-scale solar capacity targets in MW.

Data collected from various policy documents. For methods used in deriving utility-scale solar targets, refer to Section 3.2.3.

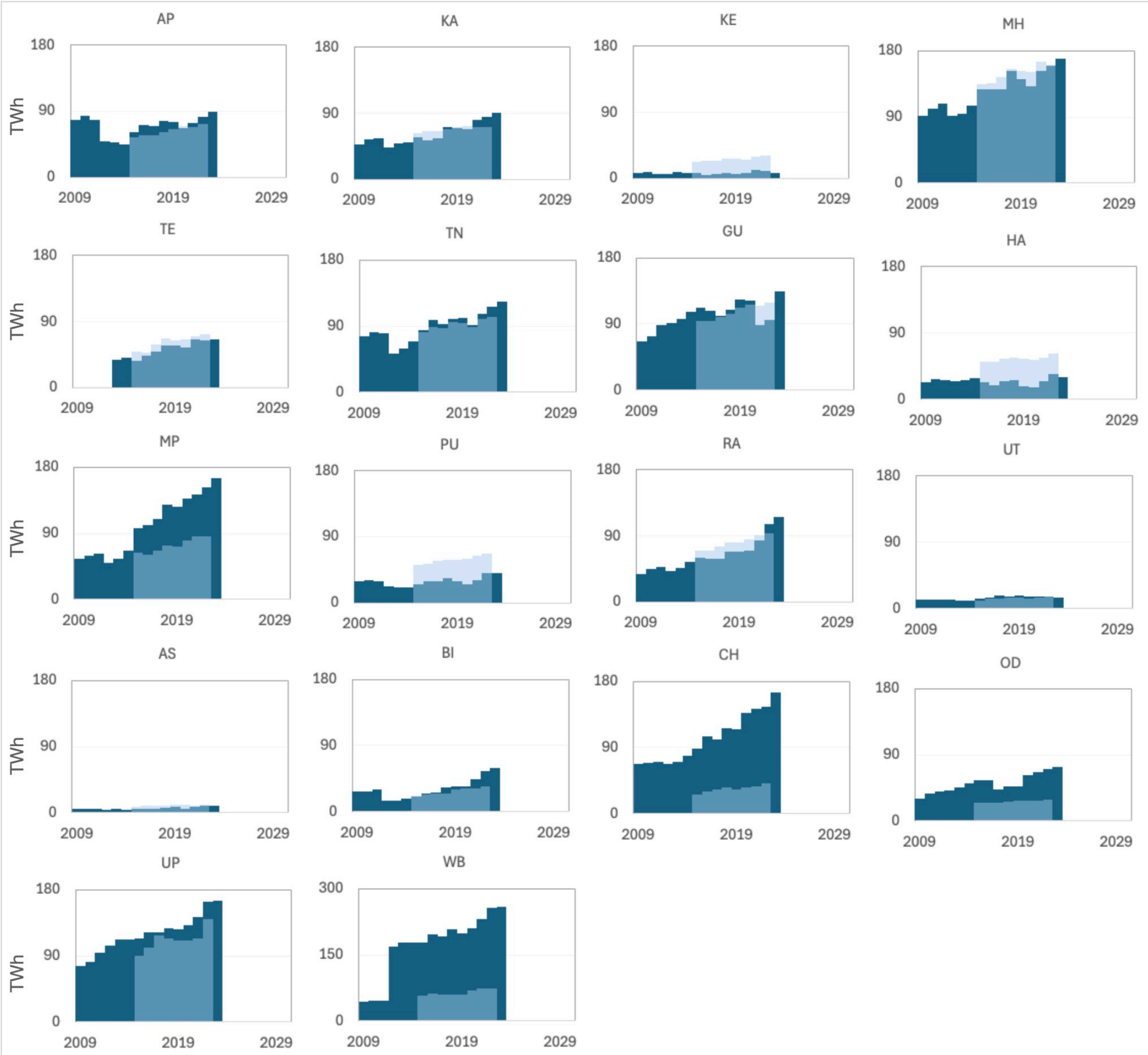

Figure A.7: Total power generation (dark blue) versus total power purchase (light blue) across Indian states.

The figure highlights state-level power deficits and surpluses over the last 15 years. North-eastern states like Chhattisgarh, West Bengal, Odisha, and the northwestern state of Madhya Pradesh have consistently shown surplus generation, driven by their concentration of thermal power plants. In contrast, smaller states such as Punjab, Assam, Kerala, and Haryana have faced persistent deficits and relied heavily on electricity trade to meet demand. Data source: ICED (2025)

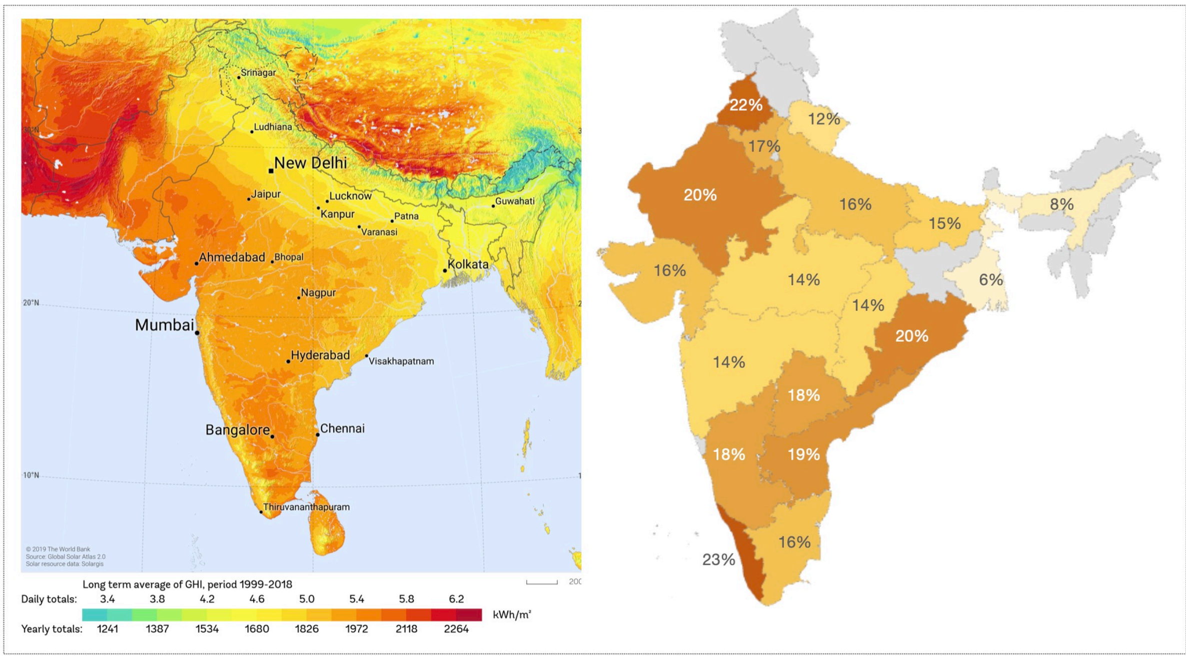

Figure A.8: Global Horizontal Irradiance (left) and calculated capacity utilisation factor of solar power plants in India.
Source: GHI - World Bank, CUF - Own calculations based on installations and generations between 2015-2024

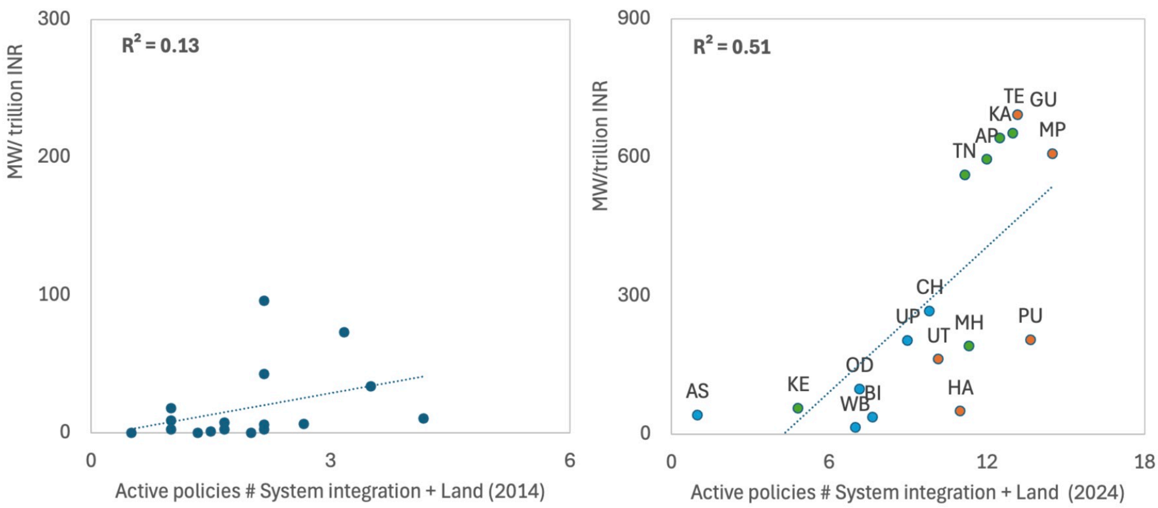

Figure A.9: Relation between the density of system integration and land-use/acceptance policies and solar deployment across states.

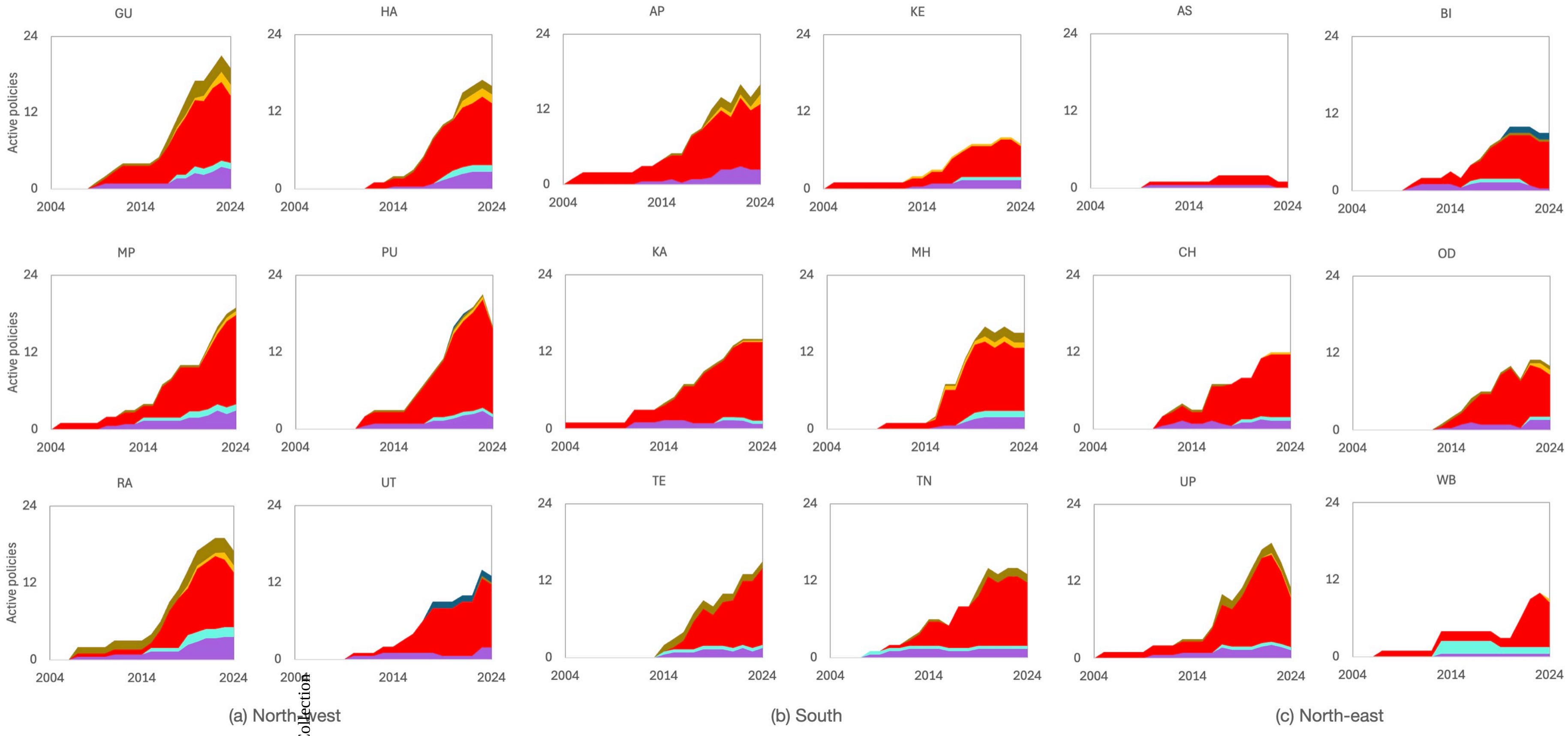

Figure A.10: Evolution of policy priorities in the active policy mix across Indian states.
The first two columns represent northwestern states, the next two represent southern states, and the final two represent northeastern states.

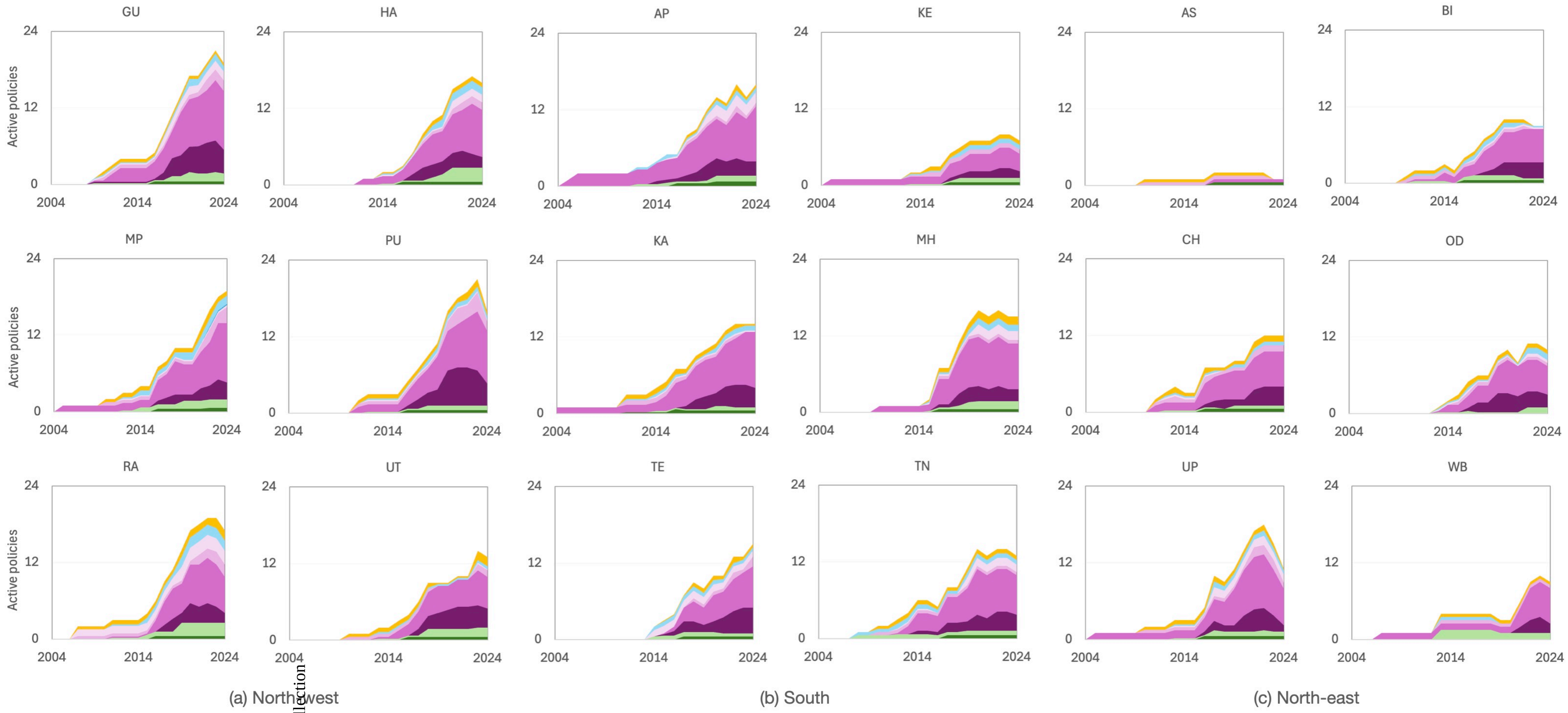

Figure A.11: Evolution of policy instruments in the active policy mix across Indian states.
The first two columns represent northwestern states, the next two represent southern states, and the final two represent northeastern states.

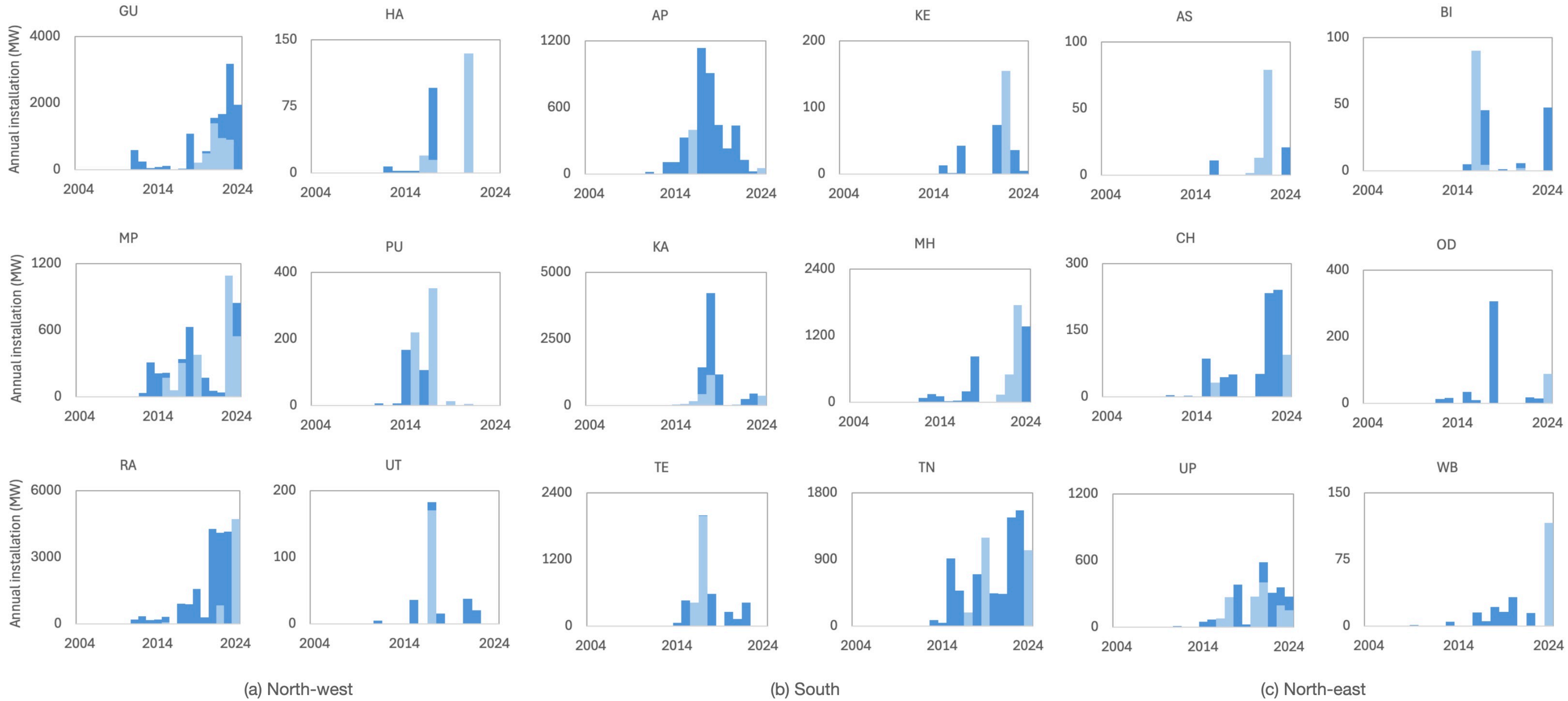

Figure A.12: State-wise installations from auctions by national off-takers (dark blue) versus state off-takers (light blue).

Own calculations based on auctioned capacity data from the Bridge to India Tender database and installation data from MNRE. Allocated capacities in auctions are assumed to be installed after two years. The first two columns represent northwestern states, the next two represent southern states, and the final two represent northeastern states.

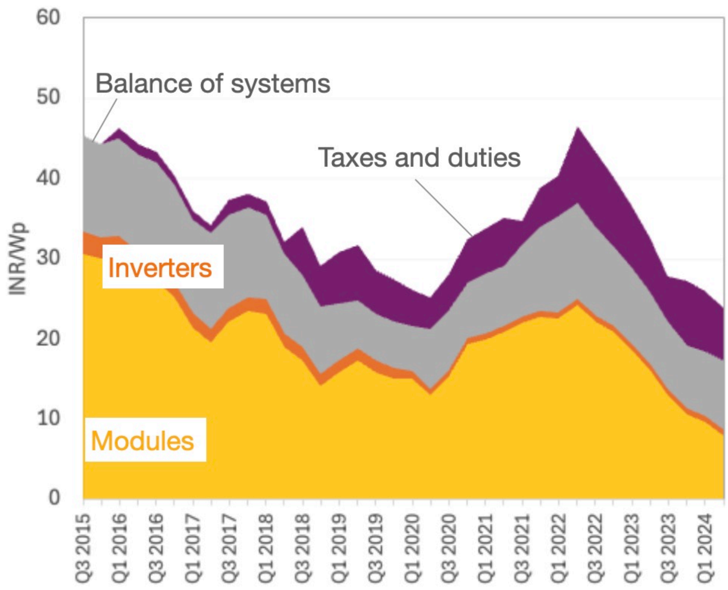

Figure A.13: Change in solar CAPEX due to implementation of the 2018 import tax. Source: Bridge To India (2024)

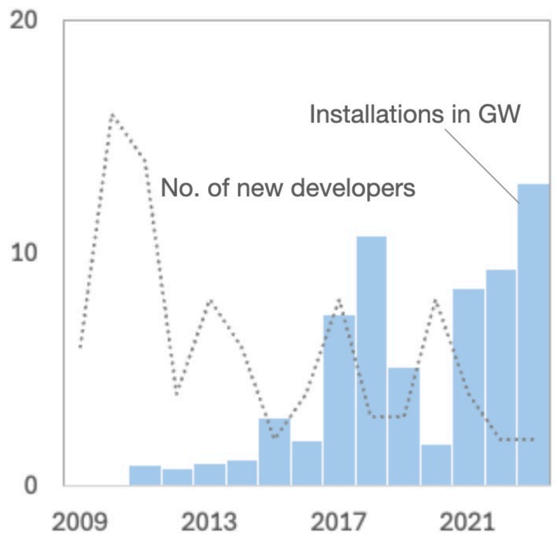

Figure A.14: Number of new developers entering the solar market over time.