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Battery storage manufacturing in India: A strategic perspective

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A B S T R A C T

India's ambitious decarbonization goals for 2030 – 40% of electricity generation capacity from renewable energy and 30% of automobile sales as electric vehicles – are expected to create significant demand for battery storage in India. This provides an opportunity for India to become a leader in battery storage manufacturing. However, setting up appropriate conditions for the same would require an understanding of the typical barriers faced by a country's industry in establishing manufacturing competency. To do so, this study first develops a critical barrier framework by identifying and assimilating barriers to industrial development, via a comprehensive literature review on industrial development. This framework consists of barriers that fall under three main categories, namely Getting to Scale, Resources and Infrastructure, and Global Competitiveness; and it posits that all these barriers need to be overcome for an industry to be successful. This framework is then verified using international and Indian case studies on the automobile, pharmaceutical, and solar photovoltaic industries. This framework is subsequently used to provide suggestions to policymakers for consideration, including the following: First, clearly identifying target markets; second, potentially exploring the use of protectionist measures; third, enabling entry in the value chain closer to the end product, while ensuring appropriate access to infrastructure and resources; and, eventually moving up higher in the value chain, via a focus on research and development.

1. Introduction

1.1. Background

India is one of the few countries with a Nationally Determined Commitment (NDC)[1] that is consistent with the 2-degree Celsius emission goal set under the Paris agreement [15]. Some of the major milestones under India's NDC are the country's renewable energy targets of 175GW by 2020 and renewable energy as 40% of installed power generation capacity by 2030 [86].

However, renewable energy generation is variable, intermittent, and inflexible by nature. Given the predominantly inflexible nature of the Indian power grid due to high reliance on coal-based generation (which has limited flexibility due to inherent technical limitations, such as limited ramp rates due to high thermal inertia) and lack of gas-based generation (which is predominantly used worldwide as a thermal flexible resource), higher renewable penetration under India's NDC will likely result in requirements of various flexible technologies [85].

One such technology that is gaining momentum globally is battery energy storage, specifically Lithium (Li) ion batteries. This is mainly attributed to the rising demand for battery-powered electric vehicles globally [79]. According to an estimate (Fig. 1), energy storage global demand is projected to rise from 9GW/17GWh in 2018 to 1,095GW/2,850GWh by 2040 with India emerging as the third-largest market [8].

The Indian government has recognized this market potential and has approved the *National Mission on Transformative Mobility and Battery Storage*, a roadmap for implementing battery manufacturing in the country [38]. This involves a five-year phased plan for implementing Giga-scale manufacturing capacities with an initial focus on battery module and battery pack assembly subsequently followed by battery cell manufacturing.

But many countries, such as the United States and South Korea, are well ahead of India in terms of research and manufacturing experience on battery technologies, with companies such as Tesla and LG Chem in the forefront of the industry [41]. These countries have developed industrial competency in such products using a top-down approach (Fig. 2 in)[2], where investments in research & development (R&D) are followed by the commercialization of technology and development of full-fledged manufacturing prowess.

Conversely, an alternate pathway to developing industrial competency is a bottom-up approach where the development of manufacturing competency first can help a country capture market share (Fig. 2); and, the country can then move up the value chain to more research intense activities. This approach can also be categorized as technology catch-up, which has been a well-demonstrated phenomenon by various industries in different countries such as the automobile

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[1] Abbreviations have only been used where necessary. A list of all abbreviations can be found in the Appendix (Section 6).

[2] Top-down vs. bottom-up is strictly in reference to the Figure 2 which is used as an illustration to show the approach taken by developing countries for technology catch-up.

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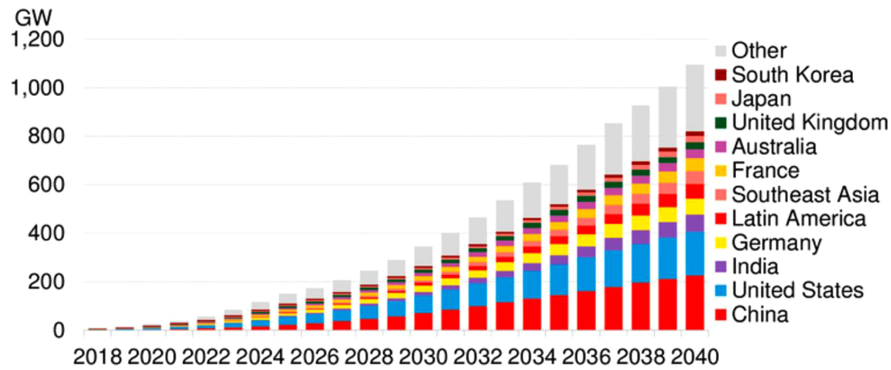

Fig. 1. Global Cumulative Energy Storage Installations [8]

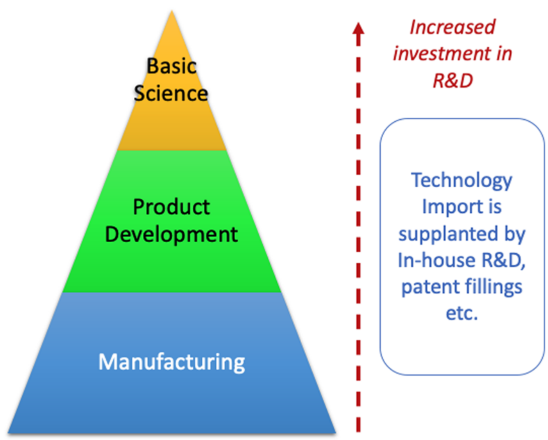

Fig. 2. Representation of a bottom-up approach to developing industrial competency

industry in Korea, electronics industry in Taiwan, and photovoltaic (PV) solar industry in China [43].

Given India's limited experience in developing new generation battery technologies (such as Li-ion) and its late arrival in the industry, the bottom-up approach may be more appropriate [69]. That is, by taking this approach India can start competing lower down in the value chain, while also developing capabilities in the upstream. However, a key question in this context is: *How should the Indian policymakers approach developing industrial competency in battery manufacturing via a bottom-up approach in a strategic manner?* This serves as the rationale for our study to provide strategic input to policymakers, specifically by developing and verifying a theoretical framework that highlights the minimum set of barriers that need to be overcome for obtaining industrial competency in battery storage.

Ideally, such a framework must address various factors: first, the approach the industry should adopt for its development i.e. top-down vs. bottom-up; second, the industry's or the nation's internal capabilities to develop the market i.e. resources and infrastructure; third, the impact of external-market based factors such as global competition on the development of the domestic industry. To the best of our knowledge, such a comprehensive framework does not exist within the academic domain. Further, we are not aware of any strategic analysis of the development of the battery storage industry in developing countries, including India. We aim to address these gaps in this study.

1.2. Related work

In this section, we examine existing literature on industrial development and demonstrate that most of this discussion revolves around the development of research and associated internal capabilities. Consequently, we identify literature on a manufacturing-oriented approach to industrial development and justify its use within our broader framework, which also borrows from management science. In addition to this, we review literature that focuses specifically on energy storage development within geographies and find a lack of strategic frameworks, which is precisely the focus of our paper.

Establishing industrial competency at the national level is a very complex issue that mainly entails the process of accumulating knowledge and capabilities by various actors that are intertwined by numerous interactions [14]. Such knowledge accumulation can occur either through research and development or through learning by doing. The theory of *National Innovation System* (NIS) is closely related to the former and it is critical to the growth and development of a country [18, 52]. We find that such a focus on developing a NIS (specifically R&D and related components) has been observed in the literature on developing industrial competency in renewable energy and energy storage sectors [30, 33, 35, 39]

While developing such a research-oriented system would very likely provide a fertile ground for the development of industries at a national level, it may not necessarily be the only way to do so. This is especially true in the case of developing countries where resources are limited for such purposes. That is, the traditional approach of developing a NIS, as discussed by Herstatt et al. [31], may not apply to the case of India attempting industrial competency in battery storage.

Over the years, there have been numerous cases where developing countries have been able to develop industries through an alternate process called technology catch-up [43, 48]. According to Lee [43], this involves duplicative imitation followed by creative imitation and real innovation as the country gains traction. This approach is mainly focused on knowledge accumulation through learning by doing and it is very much in-line with the bottom-up approach to industrial competency, where the industry first starts with developing manufacturing capabilities and then moves up the value chain to research and development (Fig. 2).

Most recently, China's development of its renewable energy industry by adopting such an approach has been exemplary. The country's emergence as the dominant player in the solar PV industry, despite its late entry, was completely unforeseen, especially when countries such as the United States were significantly ahead in terms of research and development [35]. The same is also true for Chinese firms in the wind turbine industry, where they have captured large market shares despite their late entry [33, 42]. Given the similarities between these industries to India's present position concerning the batter storage industry, this approach appears appropriate as the basis for prescribing recommendations for the Indian battery storage industry in this study.

Beuse, Schmidt and Wood [6] have recently applied the bottom-up approach as a suggestion for the development of the battery storage industry in Europe. They recognize the following: first, battery cells are strategic and therefore need to be focused on; second, leapfrogging to advanced cell technologies may not be possible due to their complex nature; third, catching up is realistic and possible. They then suggest the development of a technology-smart policy that is focused on catch up first, followed by a comprehensive development of the NIS in parallel. However, they fail to provide a strategic framework against which their recommendations can be tested.

Similarly, the Indian government has suggested the bottom-up approach in its latest battery storage industry development roadmap [37]. But it also lacks a rigorous strategic approach based on the minimum set of conditions (which typically address corresponding barriers) required to achieving manufacturing competency. In the absence of such a strategic approach, India failed to obtain industrial competency in solar [68] and is likely to repeat the struggle in battery storage. Such an assessment based on a critical barrier framework for any country, to the best of our knowledge, also does not exist within any academic domain. This provides the appropriate context to introduce our study and our contribution to this domain.

1.3. This study

This study makes the following important contributions, which are discussed in detail subsequently:

- It provides a strategic outlook on the development of industrial competency, with a focus on India's battery storage industry.
- It develops a critical barrier framework, as sufficient and necessary, for developing industrial competency.
- It verifies this critical barrier framework, using a comprehensive set of case studies, covering various countries and industries.
- It then provides a set of recommendations to the Indian policymakers on developing industrial competency in battery storage manufacturing.

This study provides a strategic outlook on the development of industrial competency, with a focus on India's energy storage industry by prescribing a novel critical barrier framework; which is a minimum set of barriers which, when overcome, can result in the successful development of an industry. While the general concept of a critical barrier framework is known, our contribution is the development of this framework specifically for the development of industrial competency in a bottom-up manner.

We develop this critical barrier framework for industrial competency based on our learnings from various literature avenues on industrial development and management sciences. Specifically, we examine concepts such as Critical Success Factors (CSF), industrial catch-up, and national competitiveness.

We then verify this critical barrier framework using a set of industrial case studies, which provide us with the required sample for the case study method [77]. These industries are selected such that there are enough variations in the dependent variable as well as independent variables [71], where the former is represented by the status of industrial success (i.e. successful vs struggling) and the latter are represented by the modes through which this status was achieved. Our learnings from this analysis are then utilized to provide strategic suggestions on the various approaches Indian policymakers can consider to establish industrial success in battery storage manufacturing.

2. Methods and data

This section delineates the various methodological steps involved in our study. As discussed earlier, we adopt a commonly used social science research method of case studies, with the cases carefully selected to provide ample variation across the dependent and independent variables [71, 77]. This section starts with identifying a set of metrics to identify successful and struggling industries (Section 2.1) from the case study sample (Section 2.3). This is followed by introducing the novel critical barrier framework (Section 2.2), which is then verified using the selected cases of successful and struggling industries (Section 3).

Table 1
Competency metrics and respective success thresholds

National Success Metrics	Success Threshold
Contribution to Gross Domestic Product (GDP)	10%
Contribution to Manufacturing GDP	10%
Contribution to Domestic R&D Expenditure	10%
International Success Metrics	**Success Threshold**
Global Manufacturing Share (by volume)	10% or Ranked within the top 10

2.1. Determining effectiveness

This sub-section discusses the metrics chosen to determine the *dependent* variable i.e. success of an industry, which is used to determine case studies that are representative of successful and struggling industries. These metrics are divided into two groups - *National Success Metrics* and *International Success Metrics*. The former is used to determine industrial success at a domestic level whereas the latter is used for assessing success at an international level. For each case study, at least one of the metrics from the national level and international level must meet their determined threshold levels for that industry to be considered successful at the respective level. Further, an industry is considered an overall success if it's found to be successful at either of the two levels.

The metrics that were chosen to determine industrial competency are aimed to cover a wide range of potential impacts of the industry and are typically used in broader industrial competency literature. The metrics under *National Success Metrics* are *Contribution to Gross Domestic Product; Contribution to Manufacturing GDP*; and *Contribution to Domestic R&D Expenditure*. The metrics associated with GDP are commonly used indicators that specify the value added by the industry's output to the country's economy [83]. *Contribution to Domestic R&D Expenditure* is an important metric that is used to determine an industry's contribution to the nation's total expenditure on R&D, and thereby to its NIS [22]. The metric used as the *International Success Metrics* is *Global Manufacturing Share (by volume)*. This metric can indicate not only the percentage of global production captured but also the position of the industry in comparison to its international competitors.

Success for industries is determined by assessing each case based on these metrics and their respective thresholds at the national and international levels (Table 1). Note that all the thresholds are at 10%, i.e. an industry must have at least 10% market share to be considered a significant market player. This threshold, which also leads to the "ranked within the top 10" condition, has been construed from basic economic principles [75].[3] Although quantitative metrics are used as our primary means for determining industrial success, qualitative reasoning is used in cases where data on such metrics could not be obtained.

2.2. Diagnosing effectiveness

This sub-section describes how the critical barrier framework is developed and applied to the selected case studies for diagnosing their effectiveness or industrial success. The critical barrier framework is built by combining learnings from two diverse strands of literature, namely industrial development and management science. In particular, the individual elements in our framework have been derived from the

[3] According to this theory, a firm would need have at least 10% market share to be considered significant in a well-developed market. Assuming that a market has equally significant firms, each holding a market share of at least 10%, the market would have at most 10 firms (Table 1).

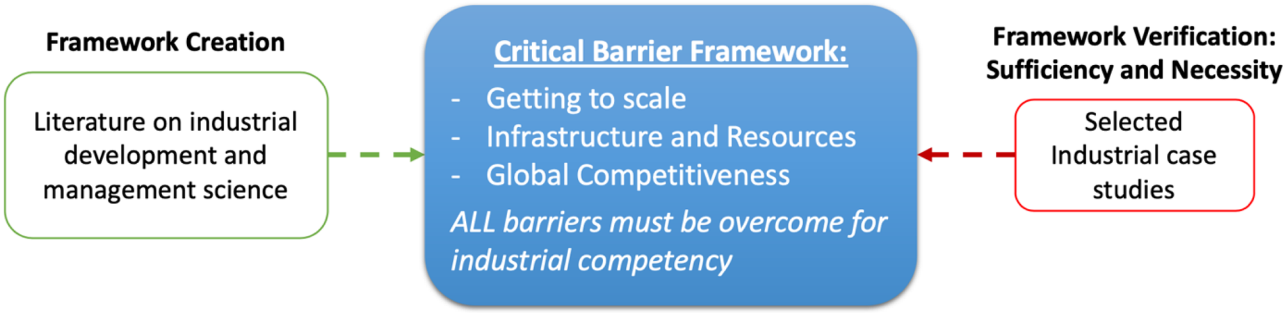

Fig. 3. A graphical representation of diagnosis effectiveness

literature on industrial development competency, whereas the structure for the framework is taken from a concept in management science, as described below.

We assess the vast literature on the concept of *industrial catch-up* [7, 14, 20, 43, 48, 53] and Porter's *Diamond Theory of National Advantages* [58] to derive the elements that constitute our framework. We posit that the existing literature on industrial science while highlighting various elements comprehensively, falls short in structuring these elements into a barrier framework that can be used by policymakers. We derive motivation from the management science concept of Critical Success Factors (CSF) to build our critical barrier framework for industrial competency. CSF describes such barriers as the minimum set of areas or objectives that need to be addressed to ensure the success of an organization or project [64]. A similar concept of a "gateway barrier" has also been used by Comello, et al. [16] in their study on micro-grid deployment in India.

Since this secondary research is based on a comprehensive literature review, including theoretical foundations as well as their application to case studies of various industries in different countries, we are confident of the sufficiency of our framework; that is, the elements identified within our framework are key to developing industrial competency.

We further posit that all the conditions embedded in the framework are necessary; i.e., they need to be met to achieve success in the long-term and (conversely) that not meeting even one of the conditions may result in an industry that struggles to meet industrial success in the long-term. That is, these conditions, which form the *independent* variables for our study, are both necessary and sufficient (see Fig. 3).

This framework is then verified by an in-depth evaluation of the selected case studies. Once the framework has been verified through the case studies, it is used as a template to build relevant policy suggestions in the context of developing the energy storage manufacturing industry in India.

According to our framework for industrial success, three critical barriers need to be met, and the failure to meet any one of these would result in a struggling industry:

1 Getting to Scale:

This essentially relates to a fledgling industry developing and maturing to reach large scale manufacturing. The microeconomic theory of attaining cost advantages through increased production volumes is one that has been assessed and identified to play an important role in various contexts. Its effect in enabling catch-up by countries such as Germany has been documented by economic historians such as Alexander Gerschenkron [20].

An appropriate and significant demand is a critical factor in attaining large scale manufacturing. Although Malerba and Nelson [48] identify export demand to be key in the catching-up process, they also acknowledge that large enough domestic demand, especially in cases of countries with high growth rate and per capita income, will enable industries to accumulate capabilities.

Industries in such economies may also face challenges in capturing said demand given the cost advantage global incumbents may have due to volume manufacturing (another term for getting to scale) which has been identified as a *structural barrier to entry* [53]. Since learning (both at the firm and national level) takes time, the government can play an active role in safeguarding infant domestic firms through measures such as rent management and distorting international market signals [14]. Providing such a protected opportunity to learn is fundamental to the development of an infant industry.

2 Infrastructure & Resources:

This is an area that receives much attention in the existing literature – i.e., creation of a broader National Innovation System, which not only allows for support for research and development but also focuses effort on the overall value chain leading to deployment [18, 66].

While traditional barriers to industrial development such as lack of skilled labor, availability of reliable transport, and cheap power can exist in a country such as India, these can be potentially addressed by entrant firms themselves in the short run, particularly if they have access to significant demand ([31,91]). However, in the long run, as more domestic firms start competing and reducing profit margins, the government must address these concerns through setting up appropriate educational policies, development of Special Economic Zones (SEZs), etc. Developing research capabilities (at the firm and state level) can also have long term impacts on not just the competitiveness of existing industries, but also of that of upcoming industries.

3 Global Competitiveness:

Lastly, industrial development must be carried out keeping in mind long-term global developments and competition on these fronts. While it is possible to capture domestic markets in the short-term using protectionist measures (as discussed in *Getting to Scale*), in the long-term industries need to stay dynamically competitive in global markets.

An important aspect of achieving this is through constant innovation [20, 58]. That is, firms and industries must not only bring about minor innovations through learning by doing, but they must also try to capture higher value-added process in the manufacturing stream which may be more research-oriented.

Governments can support firms in achieving global competitiveness by various means such as introducing competition among the domestic players by removing any existing protectionism, stimulating learning and capability formation through investments in research at universities and public organizations [14, 48, 58].

In summary of the critical barrier framework, we note that these three critical barriers are interlinked with each other. For example, to catch up and gain a footing in the global market, the industry needs to achieve economies of scale by capturing significant demand. This could also be a prerequisite to remain competitive with international firms. Further, the presence of adequate demand may directly influence the development of infrastructure on a case by case basis, even though the latter may also be developed independently by the state. As another example, in a global market (i.e., no protected domestic markets), reaching global competitiveness may be necessary to get to scale. Such relations have also been identified in our discussions of the case studies.

Another important aspect of our framework is that its manufacturing centric approach towards industrial development is applicable for industries that starts with a focus on product development and later shifts to process improvements once a dominant design is established [7]. Battery storage industry can be categorized as such an industry because specific battery chemistries/types retain certain dominant product designs [46].

We also acknowledge the importance of the political systems and role of the state in the formulation and execution of industrial development policies but we believe that a thorough consideration of the same is beyond the scope of the paper [49]. We assume that the framework and policy suggestions within this paper can be implemented in the region of interest (i.e. India). This assumption is reasonable considering India's history of adopting similar policies for developing its industries such as its automobile and pharmaceutical industries (this is explained in detail under their respective case study).

2.3. Selecting case studies

Based on the set of metrics in Section 2.1, and the critical barrier framework in Section 2.2, a total of five cases have been selected (Table 2). Out of this sample, certain cases pertain to industries within India (i.e. the country of interest) and certain cases pertain to the broader energy industry which is closely related to battery storage (e.g., solar PV). Details on the cases studies are in the Appendix (Section 6).

Our case selection is intended to capture any variances that could result because of changes in region or industry [71]. The case selection also ensures that there is ample variation across success metrics developed in Section 2.1 as well as factors driving success developed in Section 2.2. This variation is key to increasing confidence in our framework. These cases are then further studied through qualitative case studies to verify the theoretical framework of critical barriers, as developed in Section 2.2.

3. Results and discussion

3.1. Results

In this section, the industries introduced in Section 2.3 are now determined as successful or struggling, based on the competency metrics developed in Section 2.1. Most of the data is gathered using the references used in the case study descriptions in the Appendix (Section 6).

Note that, in many cases, certain metrics are either not applicable or simply not used (e.g., due to lack of data or due to simply being not needed for our analysis) in determining its success; and therefore, are marked as not applicable (N/A). Table 3 provides a summary of the evaluation results, which are then examined in more detail in Sections 3.1.1 and 3.1.2.

Table 2
Selected industries and their respective regions

Industry	Region/Country
Automobile	India
Pharmaceutical	India
Solar Photovoltaic (PV)	China
Solar PV	United States
Solar PV	India

3.1.1. Successful industry cases

3.1.1.1. Indian automobile industry. From the various *National Success Metrics* (Table 4), it is evident that the automobile industry plays a significant role in India, especially in its manufacturing sector. Further, the country has grown to become one of the top producers of automobiles on the global front as well. Given that at least one of the success metrics meet the threshold limits – i.e. *Contribution to Manufacturing GDP* > 10% and *Global Manufacturing Share Rank* < 10, the industry can be considered an industrial success on both the domestic and international levels.

3.1.1.2. Indian pharmaceutical industry. The pharmaceutical industry in India is one of the top manufacturers of generic drugs in the world. The industry is also slowly moving towards higher-value activities in the value chain such as research and development. This is evident from the national metric – *Contribution to Domestic R&D Expenditure* indicating more than $1/3^{rd}$ (i.e. > 10%) of the expenditure coming from the pharmaceutical sector (Table 5). Similarly, the global metric shows that India is one of the top manufacturers of pharmaceutical products in the world. Given that at least one of the success metrics meet the threshold limits – i.e. *Contribution to Domestic R&D Expenditure* > 10% and *Global Manufacturing Share Rank* < 10, the industry can be considered an industrial success on both the domestic and international levels.

3.1.1.3. Chinese solar PV industry. The global solar PV industry is presently dominated by Chinese manufacturing firms accounting for a total of 71% *Global Manufacturing Share (by volume)* (Table 6). Given this metric meets the threshold limit – i.e. > 10%, the industry can be considered an international success. For determining national success, on the other hand, a qualitative approach is used due to a lack of data on specific metrics. We argue that given China is the largest market for solar PV, the significant global market share captured by Chinese manufacturers would have been possible only if they were able to cater to the large local demand as well. Therefore, this can be taken as an indication of national success as well.

3.1.2. Struggling industry cases

3.1.2.4. United States solar PV industry. Even though the U.S. was one of the first countries to develop and commercialize solar PV technology, domestic manufacturing could not maintain a strong footing in the global market. As of 2018, solar PV module deployment in the United States accounted for only about 1% of the Global *Manufacturing Share (by volume) (*Table 7*)*. Given this metric does not meet the threshold limit – i.e. > 10%, the industry can be considered as struggling in the global context. Further, a qualitative discussion is used to determine the national success of the industry due to a lack of data on *National Success Metrics*. Domestic deployment is one of the top markets globally accounting for a maximum of 20% global demand in the year 2016 but a majority of it was mostly met through cheaper imports. This shows that the U.S. solar PV industry is struggling to stay competitive at the national level as well.

3.1.2.5. Indian solar PV industry. The Indian solar manufacturing sector started with limited participation of firms in the early 2000s. The industry expanded at a slow pace mainly because it relied on international demand for reaching scale. This is reflected in the international metric which shows that only 2% of the *Global Manufacturing Share (by volume)* in 2018 was located in India (Table 8). Since this metric is less than its success threshold i.e. > 10%, it can be considered to be struggling at the international level. Further, late entry into the market by domestic manufacturers also

Table 3
Summary of case study evaluation

Case Studies	Successful		Criteria	
	National	International	National	International
Indian Automobile Industry	Yes	Yes	Contribution to Manufacturing GDP = 49% (i.e., > 10% threshold)	Global Manufacturing Share (by volume) = Rank 4 (i.e., within top 10)
Indian Pharmaceutical Industry	Yes	Yes	Contribution to Domestic R&D Expenditure = 37.36% (i.e. > 10% threshold)	Global Manufacturing Share (by volume) = Rank 3 (i.e., within top 10)
Chinese Solar PV Industry	Yes	Yes	Qualitative analysis only	Global Manufacturing Share (by volume) = 71% (i.e., > 10% threshold)
United States Solar PV Industry	No	No	Qualitative analysis only	Global Manufacturing Share (by volume) = 1% (i.e., < 10% threshold)
Indian Solar PV Industry	No	No	Qualitative analysis only	Global Manufacturing Share (by volume) = 2% (i.e., < 10% threshold

Table 4
Success metrics and respective values – Indian automobile industry

National Success Metrics	Value	Source
Contribution to Gross Domestic Product (GDP)	7.5%	[26]
Contribution to Manufacturing GDP	49%	[26]
Contribution to Domestic R&D Expenditure	14.7%	[73]
International Success Metrics	**Value**	**Source**
Global Manufacturing Share (by volume)	Ranked 4^{th} (5.5% share)	[55]

Table 5
Success metrics and respective values – indian pharmaceutical industry

National Success Metrics	Value	Source
Contribution to Gross Domestic Product (GDP)	2%	[1]
Contribution to Manufacturing GDP	12%	[1]
Contribution to Domestic R&D Expenditure	37.36%	[73]
International Success Metrics	**Value**	**Source**
Global Manufacturing Share (by volume)	Ranked 3^{rd}	[62]

Table 6
Success metrics and their respective values – Chinese solar PV industry

National Success Metrics	Value	Source
Contribution to Gross Domestic Product (GDP)	N/A[a]	
Contribution to Manufacturing GDP	N/A	
Contribution to Domestic R&D Expenditure	N/A	
International Success Metrics	**Value**	**Source**
Global Manufacturing Share (by volume)	71%	[29]

[a] Values marked as N/A are not available

Table 7
Success metrics and respective values – United States solar PV industry

National Success Metrics	Value	Source
Contribution to Gross Domestic Product (GDP)	N/A	
Contribution to Manufacturing GDP	N/A	
Contribution to Domestic R&D Expenditure	N/A	
International Success Metrics	**Value**	**Source**
Global Manufacturing Share (by volume)	1%	[87]

meant competing with advanced manufacturers from other countries such as China and Japan. This, in turn, resulted in significant local demand being captured by imports. Based on this, it can be concluded that the industry is struggling on the domestic level as well.

4. Discussion

In this section, the cases of successful and struggling industries are used to test the critical barrier framework (see Section 2.2), which in turn is used to develop suggestions for the development of battery storage manufacturing competency in India. Note that the data used in this analysis is mostly gathered from the detailed case studies in the Appendix (Section 6). Table 9 shows a summary of the result from testing the critical barrier framework, with "partial" indicating that the industry has been able to overcome some of the issues related to the corresponding barrier.

Table 8
Success metrics and respective values – Indian solar PV industry

National Success Metrics	Value	Source
Contribution to Gross Domestic Product (GDP)	N/A	
Contribution to Manufacturing GDP	N/A	
Contribution to Domestic R&D Expenditure	N/A	
International Success Metrics	**Value**	**Source**
Global Manufacturing Share (by volume)	2%	[87]

Table 9
Critical barrier framework verification results

Case Studies	All Critical Barriers Met?	Unmet Critical Barriers
Indian Automobile Industry	Yes	None
Indian Pharmaceutical Industry	Yes	None
Chinese Solar PV Industry	Yes	None
United States Solar PV Industry	No	*Getting to Scale (partial)*; Global *Competitiveness*
Indian Solar PV Industry	No	*Getting to Scale; Infrastructure & Resources (partial); Global Competitiveness*

4.1. Successful industry cases

4.1.1. Indian automobile industry

The Indian automobile industry can be viewed as successful given that it addresses all potential barriers identified in Section 2.2. This is discussed in detail below.

Getting to Scale: During the inception of the automobile industry in India, the country had various protectionist policies that restricted entry into the market and guaranteed demand. These policies included the following: imposing a ban on assembly shops that did not have any manufacturing component, implementing import restrictions, and licensing systems. Policies such as the licensing system hindered the growth of the industry as it restricted the entry of private firms in the market. Subsequent easing of such policies by the 1980s allowed the industry to expand through the formation of joint-ventures thereby allowing them to slowly address a massive untapped domestic demand. Further economic liberalization starting in 1991 resulted in more competition which resulted in the lowering of prices through scale as domestic demand increased.

Infrastructure and Resources: Many of the first-mover firms faced multiple issues in terms of transportation, power, and skilled labor. Most of these were addressed by the firms themselves through various means such as investing in reliable power generation, adjusting inventory levels to mitigate any transportation delays, domestic sourcing, and conducting labor training [27, 28]. Starting in 2000, the Indian government has aimed to address this with the creation of Special Economic Zones (SEZs) [82]. These regional clusters not only provide financial incentives such as tax breaks but also provides common infrastructure facilities for setting up manufacturing centers.

Global Competitiveness: The Indian government has been cognizant of the influence of international firms in the process of industrial development. Initially, automobile assemblers were allowed to simply import and assemble knockdown units. This negatively impacted the development of a domestic manufacturing program and hence forced the government to implement protectionist policies. Many of these policies were eventually eased through controlled foreign direct investments (FDIs) and import taxes, which resulted in slowly opening the domestic market to international firms. This has brought about a healthy competition to the market which drives improvement and innovation among all manufacturers. Presently, India is the fourth largest automobile market in the world with domestic firms capturing top positions in domestic as well as certain global market segments (Table 4).

4.1.2. Indian pharmaceutical industries

The Indian pharmaceutical industry can be viewed as successful given that it addresses all potential barriers identified in Section 2.2. This is discussed in detail below.

Getting to Scale: One of the primary reasons why the Indian government decided to limit product patent laws in the 1970s was to promote re-engineering of these products, producing them at a cheap cost and in large volumes under the category of generic medicines. These “first in class production processes” for cheap generic drugs enabled domestic manufacturers to address the healthcare needs of not only millions within the country, but also globally [88]. Capturing such a price-sensitive market segment has given domestic manufacturers a strong footing in the global market.

Infrastructure and Resources: Public research institutions have played a very important role in diffusing skilled labor and knowledge to private firms within this industry. Many of the people who have started private firms within this industry started their careers in the public domain [88]. Also, larger firms have themselves invested in training their employees with requisite skill sets. The formation of SEZs for chemical manufacturing at various locations in the country has ensured the availability of common reliable infrastructure. This has allowed pharmaceutical manufacturers to form major manufacturing hubs in specific areas within the country.

Global Competitiveness: One of the main motivations to removing product patents early on was the monopolistic power held by Multi-National Companies (MNCs) in the industry which kept drug prices high. The export focus of domestic manufactures to other price-sensitive markets helped in the development of the industry within the country. Despite facing tough competition from highly subsidized Chinese manufacturers currently, India continues to be the largest supplier of generic drugs in the world [36].

4.1.3. Chinese solar PV industry

The Chinese solar PV industry can be viewed as successful given that it addresses all potential barriers identified in Section 2.2. This is discussed in detail below.

Getting to Scale: The Chinese solar PV manufacturing firms had established themselves specifically to take the opportunity of an increased global demand caused due to Feed-In-Tariffs in countries such as Germany, Italy, and Spain. These firms were able to get to these markets due to the cost advantages of setting up large volumes of production capacity and receiving multitudes of direct and indirect government subsidies [80]. Some industry sources estimate that this gap could be as high as 20 to 30% in comparison to Japanese manufacturers [29]. With the reduction in demand from these regions as an aftermath of the global financial crisis and anti-dumping measures, China turned to domestic policies to ensure continued demand for the manufacturers. These markets played an important role in allowing Chinese manufacturers to expand rapidly and to achieve significant economies of scale, thereby solidifying their position in the market.

Infrastructure and Resources: An important aspect of entering into the industry was the technical know-how on the manufacturing process [48]. China's choice to manufacture crystalline silicon cells was due to the fact that the manufacturing technology was mature and the manufacturing process could be acquired on the market [12]. Initially, Chinese manufacturers imported entire production lines from European vendors, hired and trained workers to enter into the market [21, 12]. Solar PV manufacturing is also a resource-intense process requiring large amounts of land and is energy-intensive. The government ensured that these resources were provided through reallocation or heavy subsidies which greatly assisted entry of new firm into the market [23].

Global Competitiveness: The rapid expansion of the Chinese PV industry commenced to cater to rising international demand. In its initial phase, nearly 95% of Chinese manufacturing was exported to other regions with high demand. When this demand reduced, the government created local demand for the product. Significant state subsidies have also allowed Chinese manufacturers to price their products aggressively in international markets and in some cases have been found to sell at below-market prices to undercut local manufacturers [81]. This has allowed the Chinese firms to retain their cost advantage and keep their stronghold on the global solar PV markets. However, these price reductions have also resulted in significant consolidation of manufactures within China along with some top manufacturers going bankrupt [10,17].

4.2. Struggling industry cases

4.2.1. United States PV industry

The United States solar PV industry can be viewed as struggling given that it has not been able to address all potential barriers identified in Section 2.2. In particular, despite initially achieving economics of scale and overcoming traditional barriers, the U.S. industry is now struggling to compete globally. This is discussed in detail below.

Getting to Scale: The main reason for the struggle of many PV manufacturers in the U.S. has been price pressures in the global market they compete in [57]. This has been mainly attributed to imports from regions mainly in the Asian continent. An appreciable rise in local demand for solar PV only started after 2009-2010 but by then China already had significant manufacturing capacity come online (Fig. 4). In the absence of large scale domestic manufacturing in the U.S., China was able to capture a significant share of its markets.

Infrastructure and Resources: In general, it is unlikely that the US solar PV industry faced any traditional barriers such as poor transportation infrastructure and the lack of utility services. This is because the United States has been addressing many of these issues as early as the 1870s (during the period of the industrial revolution) [54].

Global Competitiveness: The United States started as the top solar PV manufacturer in the world up until the 2000s, only to be soon overtaken by Chinese manufactures. Most of the domestic demand in the U.S. has now been met using imported products. This is mainly attributed to the aggressive pricing strategy followed by Chinese counterparts. In response, the U.S. has taken active measures to stop the so-called dumping of cheap PV imports from countries such as China. Also, U.S. manufacturers have approached the World Trade Organization (WTO) to get access to projects in upcoming markets such as India but their success in capturing those markets is questionable.

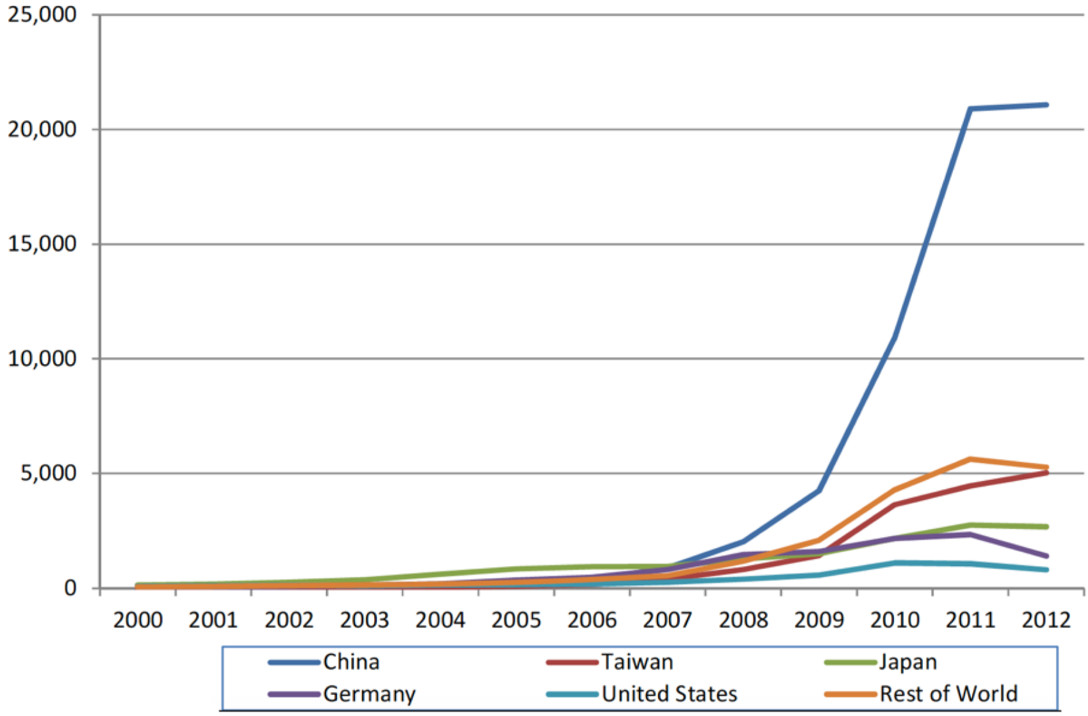

Fig. 4. Annual Solar Cell Production (MW) by Country [57]

Most recently, heavy import duties have been implemented in the U.S. to protect and attract domestic manufacturing of PV cells and modules within the country. Despite such protectionist measures, the declining market share of U.S. manufacturers suggests that they have not remained competitive in the global market.

4.2.2. Indian solar PV industry

The Indian solar PV industry can be viewed as struggling given that it has not been able to address all potential barriers identified in Section 2.2. In particular, it has not been able to achieve scale and compete globally. This is discussed in detail below.

Getting to Scale: One of the main setbacks to the Indian solar PV manufacturers is that there hasn't been any specific market which they could capture in the early days to achieve economies of scale. While the Indian government recognized this and tried to use domestic content requirements in their procurements, it was soon stopped due to WTO violations. Further, much of the manufacturing capacity in the country has remained underutilized (as high as 50%), primarily because they were uncompetitive due to lack of scale, under-developed supply chains, and insufficient funding [63].

Infrastructure and Resources: SEZs have addressed a lot of the barriers which are associated with a lack of infrastructure. As a result, nearly 40% of the solar PV panel manufacturers and 60% of the solar PV cell manufacturers are located in such special economic zones throughout the country [59]. The technology required for manufacturing has been mainly transferred from Europe and China [80]. However, due to the inability to achieve scale, the industry has not been able to invest and develop higher value research-oriented processes. Lack of such expertise could potentially affect the development of future associated industries in the country.

Global Competitiveness: By the time manufacturing facilities started coming online in India, there was already significant competition in the domestic and international markets. One of the primary reasons why domestic manufacturers have faced difficulty in competing with Chinese and other East Asian manufacturers is the lack of level playing field in terms of cost of resources, access to land, and taxes [80]. The government has not been able to address these issues adequately through vehicles such as tax breaks or subsidized utility services [40].

4.3. Implications for India storage manufacturing

It can be observed from the critical barrier framework analysis that industries that have successfully established manufacturing competency have addressed all the three barriers in various fashion.

Whereas in the case of struggling industries, the main barrier that remains to be addressed is identifying a target market and enabling economies of scale. A target market could be a domestic market that is protected through various measures against foreign competition or it could be an untapped international market with minimal competition. Overcoming this barrier, at least initially, enables the industry to establish a foothold and even overcome traditional barriers on a case-by-case basis themselves or in collaboration with the government. Eventually, the primary way to become (and stay) competitive in any market eventually depends on providing a cost-competitive product.

It is also to be noted that in cases of struggling industries, addressing one or more of the barriers may be conditional on addressing another barrier. For instance, in the case of the Indian solar PV industry, lack of adequate support from the government to level the playing field against foreign manufacturers is attributed as one of the reasons why manufacturers could not reach scale manufacturing (relation between *Getting to Scale* and *Global Competitiveness*). Similarly, in the absence of a significant market where the Indian PV manufacturers could be cost-competitive for an appreciable period, the Indian PV industry has also struggled to overcome some of the traditional barriers (relation between *Getting to Scale* and *Infrastructure and Resources*) [68]. This may have been expounded by the lack of a well-developed NIS in India.

In the case of energy storage manufacturing in India, the critical barrier framework can be used to identify and assess areas that need development to establish industrial competency. As discussed earlier (Section 1.1), the main driver of demand for energy storage is likely to be the electrification of road transport and so this is a key area to be focused on to achieve scale manufacturing. While the creation of a guaranteed demand is important in the short-term, it is also critical for the domestic manufacturers to be able to capture said demand effectively in the long-term, in particular as the Indian market opens up to global suppliers.

All the success cases studied in this paper show the presence of some form of successful government intervention to help achieve success. Such interventions are mainly aimed at giving a competitive advantage to local manufacturers against international incumbents. China's battery manufacturing industry has already advanced significantly due to local demand creation and protectionist policies by the Chinese government [45, 51]. As a result, over half of the electric vehicles sold in the world today are in China.

India is also moving in a similar direction with the recent (early 2019) approval of *Faster Adoption and Manufacturing of Electric Vehicles Phase II* (FAME II) via a combination of subsidies as well as protectionist policies. FAME II unlocks $1.4 billion in subsidies for the purchase of commercially registered vehicles, public transport fleets, and privately registered two-wheelers.

While FAME II is mainly focused on a demand-side pull, it also aims to boost local manufacturing through the 50% domestic content requirement eligibility criteria for the subsidy. In a narrower context, India may be able to justify this protectionist policy since it does not completely bar international players from entering the market. In a broader (international) context, it may still be justified given that current ambiguity around the implementation of global trade rules. In this context, China has also followed a similar policy in procuring domestically made batteries for electric vehicles manufactured in the country.

It is also important to consider the nuance involved in the manufacturing process of a product. For instance, upstream processes in solar PV manufacturing (such as crystalline silicon manufacturing) are technology-intensive as compared to downstream processes (such as component packaging) that are relatively labor-intensive and have low entry thresholds [32]. Understanding these distinctions can help Indian manufacturers enter the appropriate entry points in the value chain of the manufacturing process, depending upon their technical know-how and available capital.

While it is a good idea for India to enter into battery manufacturing by the bottom-up approach by procuring manufacturing lines, India would need to ensure that the Indian manufacturers stay competitive in the global markets in the long-term; in particular, as the domestic content requirements are reduced. This would require moving upstream in the value chain to process such as chemical processing and strengthening the elements of the National Innovation System [41]. In this vein, NITI Aayog and Rocky Mountain Institute (2017) have already recommended that Indian manufacturers start at battery pack manufacturing and then gradually move onto technology and research-heavy processes in the value chain such as cell manufacturing, electrode manufacturing, and processing of raw materials [13].

5. Conclusions and policy implications

Given the ambitious decarbonization goals of India, a significant rise in demand for battery storage is expected. The Indian government has also identified this opportunity and are in the initial stages of developing policies for domestic manufacturing.

This study aims to provide strategic guidance to policymakers to ensure the successful growth of the industry through the establishment of manufacturing competency followed by involvement in research-oriented activities.

This is done by first selecting cases of successful and struggling industries using a specified set of metrics across various regions (including India) and industries (including energy). This is followed by the creation of a critical barrier framework through literature review and uses the following elements: identifying and capturing target market(s) to achieve economies of scale; addressing traditional industrial barriers; being cognizant of changes in global markets and adapting to them

This framework is then verified through an in-depth analysis of selected industrial cases, such as the following: Indian Automobile Industry; Indian Pharmaceutical Industry; Chinese Solar PV Industry; United States Solar PV Industry; and Indian Solar PV Industry. It is found that industries that have succeeded in being competent have successfully addressed all the barriers in the framework; whereas those that have struggled have failed to overcome at least one of the barriers. The critical barrier framework is then used to give strategic direction to the development of the storage industry in India such as the following:

First, a (likely domestic) market should be identified where local battery storage manufactures can successfully achieve economies of scale. This is likely to be the electric vehicle market, appropriately complemented by the electricity system flexibility market [79]. For India to attract appropriate investments there needs to be a strong policy push such as integrated plans and clear targets [19]. In this context, India should be cognizant of its changing policy signals. For example, while there were ambitions of attaining 100% electrified road transportation by 2030, they never materialized into official targets [11]. Currently, though India aims to reach 30% electrified road transportation by 2030, it still lacks a ratified goal. Simply setting official targets for electrification of road transportation will go a long way in sending appropriate policy signals.

Second, some degree of protectionist measures from the government, at least in the early days of the industry, may provide an early competitive advantage to domestic players. This, complemented with an appropriate focus on domestic manufacturing development, can help a fledgling industry to develop independently of competition from international players. However, while doing so, India needs to be cognizant of global trade regulations since any trade disputes could be very disruptive to the industry (as evident from the present state of the Indian solar industry). Further, any such protectionist measures should only be for a finite period as open competition will eventually drive the domestic industry to become truly globally competitive. The Chinese government has followed a very similar strategy which resulted in propelling domestic battery manufacturers into some of the top manufacturers globally. In particular, the four-year-long preferential treatment for domestic manufacturers only ended recently allowing competition from the international players [34].

Third, local manufactures should identify and enter the appropriate entry point in the value chain. Starting downstream via the provision of required infrastructure and resource, achieving scale manufacturing, and then slowing working upstream over time via a focus on research and development, and becoming globally competitive. In this context, importing assembly lines would be a welcome step, with the goal of developing such lines domestically, including increasing investments in higher value upstream processes such as chemical processing. Such an approach has been followed by both Korea and China in battery manufacturing [6].

In the long-term, the Indian government could use this opportunity to improve its broader National Innovation System. This involves developing an ecosystem of various research-oriented players which can help in bringing innovation in areas such as battery chemistry. Innovation is also a crucial element in maintaining the competitiveness of domestic industries in the global context. Furthermore, spillover effects from a NIS could lead to developments in associated industries as well which can give long term competitive advantages.

This study serves as a launching point for various avenues for future investigation. Some of the future research questions are as follows: First, determining the right set of protectionist measures that is also acceptable within the broader global trade agreements. Also, the duration and extent of such protectionist measures can be determined. Second, how can India strengthen its National Innovation System to not only spur innovation around “next-generation” technologies but also in the domain of establishing manufacturing competency? Third, there are various other challenges that India may face within the battery manufacturing industry such as lack of natural resources such as minerals and ores. This needs to be considered very strategically as countries such as

China have already secured much of the supply chain associated with certain battery chemistries such as Lithium-Ion.

Author contributions

Gireesh Shrimali contributed to: Conception and design of study, analysis and interpretation of data, drafting the manuscript, and revising the manuscript.

Aravind Retna Kumar contributed to: Acquisition of data, analysis and interpretation of data, drafting the manuscript, and revising the manuscript.

Declaration of Competing Interest

This is to declare that there's no financial/personal interest or belief that could affect our objectivity.

Appendix

List of Abbreviations

FAME II	Faster Adoption and Manufacturing of Electric Vehicles Phase II
FDI	Foreign Direct Investment
FY	Financial Year
GDP	Gross Domestic Product
JNNSM	Jawaharlal Nehru National Solar Mission
MNCs	Multi-National Companies
NDC	Nationally Determined Commitment
NIS	National Innovation System
PV	Photovoltaic
R&D	Research and Development
SEZ	Special Economic Zone
U.S.	United States of America
WTO	World Trade Organization

Case study data

Indian automobile industry

This subsection provides an overview of the major developments in the Indian Automobile Industry. Post-Independence (i.e. 1947), The Indian automobile sector constituted largely of assembly shops for complete knockdown units that were imported from other countries [67]. These locally assembled imported products made it hard for the domestic manufacturing sector to gain footing in the market. The government implemented a series of protectionist measures such as imposing a ban on assembly shops without a manufacturing component, implementing import restrictions, and licensing systems, which significantly narrowed down the manufacturers in the country to a total of six players [67]. In addition to such measures, production caps on the number of vehicles manufactured also resulted in domestic manufacturing not being able to meet local demand.

Post-1980, growing local demand and the inability of domestic supply to meet this demand led the government to revise policies on permitting foreign direct investment (FDI) in manufacturing [67]. This led to the creation of major joint-ventures with Japanese manufacturers, such as Maruti Suzuki Udyog Ltd., which then resulted in technological transfers and an increase in industrial production volume. These factors along with increased utilization of domestic content resulted in cost reduction of vehicles making them more affordable to the public.

Post-1991, the liberalization of the Indian economy moved the industry towards de-licensing and deregulation. This was shortly followed by a second wave of FDI investments and a series of policy changes such as removal of production caps, increased indigenization, and stringent pollution norms. This resulted in an increase in competition which translated to improvement in product quality, creation of new product segments (such as mid-price and luxury segments), and price declines.

Today the Indian automobile industry is one of the primary drivers of the country's economy, employing over 1.1 million people directly and indirectly. Its contribution to the national GDP is approximately 7.5% and accounts for nearly 49% of manufacturing GDP of the country [26]. India was the 4th largest automobile manufacturer globally in 2018 securing top positions in segments such as tractor, two-wheeler, and bus manufacturing [50, 55].

Indian pharmaceutical industry

This subsection provides an overview of the major developments in the Indian pharmaceutical industry (Fig. 5). In the 1950s, the Indian government recognized the importance of the industry and set up public sector institutions that would receive technical and financial assistance from entities such as WHO, UNICEF, and the Soviet Union. These institutions not only created critical drugs such as penicillin but also served as a training platform for transferring knowledge to future entrepreneurs in the industry [5, 88]. The private sector mainly consisted of domestic firms that depended on bulk imports which were processed as formulations domestically, and multi-national companies (MNCs) with domestic manufacturing and research programs. Until 1970, MNCs had technological, financial, and managerial advantages which helped them give monopolistic powers in the market [5].

In the 1970s, the government introduced *The Patent Act 1970,* which stated that international patents would be valid only for processes and not for products and that these patents would have a term of only 5 years [88]. This helped Indian manufacturers in reverse engineering patented drugs and manufacture generic drugs. Additionally, the Indian government also implemented cost-plus pricing policies, local procurement of manufacturing inputs, and mandatory Active Pharmaceutical Ingredients (APIs) production. These policies resulted in a burgeoning of a generic drug manufacturing industry that produced low prices drugs catering to large domestic demand as well as that in other price-sensitive markets globally.

The economic liberalization of 1991 led to a relaxation of price control as well as higher foreign investments. India also joined the World Trade Organization *Agreement on Trade-Related Aspects of Intellectual Property Rights* (TRIPs) in 1995, which meant re-introducing product patents within 10 years. This spurred various shifts in the industry such as an increased focus on R&D and an increased export to higher-value markets such as North

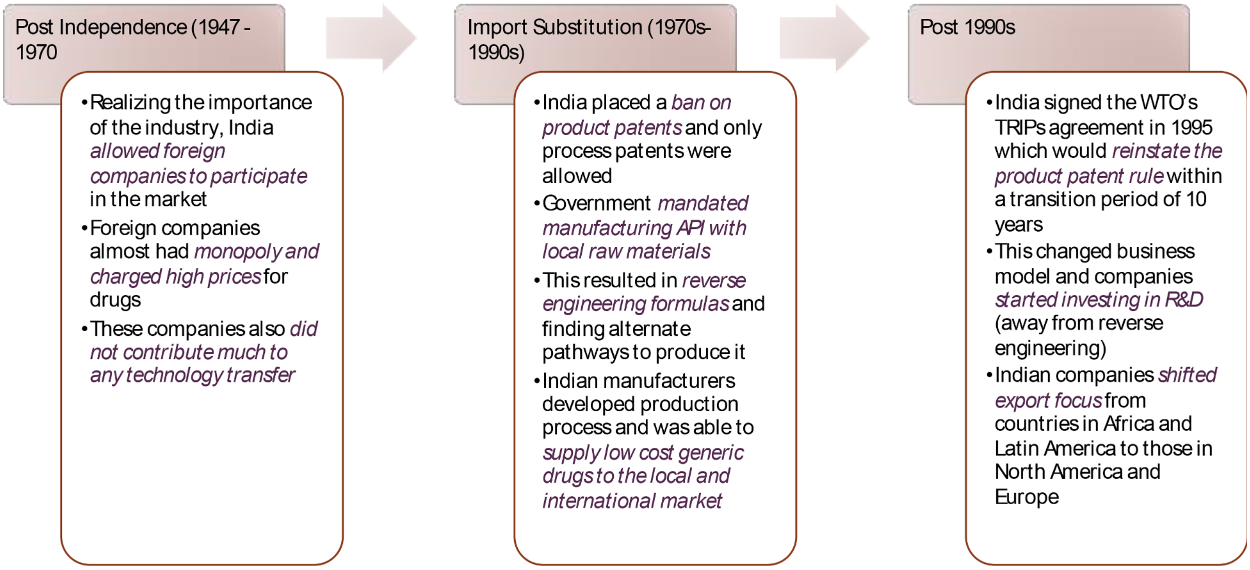

Fig. 5. Development of the Indian pharmaceutical industry

America and Europe [72].

Presently, many of the multi-national pharmaceuticals utilize Indian pharmaceutical expertise for contract research and manufacturing services. The industry has also become the largest investor of R&D in the country and is one of the fastest-growing exporters of drugs and medicine [89]. India's pharmaceutical industry is extensively studied and serves as a template for developing local pharmaceutical manufacturing capabilities in other developing countries.

Chinese solar PV industry

This subsection provides an overview of the major development in the Chinese Solar PV Industry (Fig. 6). Until 2002, China's solar PV industry was in its nascent stages with some government-funded R&D and non-civilian applications. Even though the Chinese government implemented some policies that aimed at rural electrification of western China using renewable energy, wind energy gained more traction that solar PV [24].

In 2004, European markets such as Germany and Spain implemented Feed-In-Tariffs which caused an increase in rooftop solar PV demand. Chinese manufacturers seized this opportunity and expanded their capacity rapidly to meet the rising international demand. Chinese export of finished products accounted for more than 90% of domestic manufacturing output [44]. Such a rapid expansion in production capability was possible through importing of manufacturing technology, availability of cheap loans as well as low-cost energy, and various other direct or indirect government subsidies [23].

The financial crisis of 2008 and the anti-dumping measures by Europe and the U.S. led to a sudden shrinkage in international markets causing surplus domestic production in China. This led the government to create domestic demand through *Concession Bidding, Golden-Sun Pilot Project, and Benchmark Feed-in Tariff,* to absorb excess domestic production capacity; and prop the PV manufacturing sector [32]. As a result, the annual PV addition in China increased from 40MW in 2008 to 4500MW in 2012 [90]. Many manufacturers have also moved up the value stream to vertically integrate the upstream process (i.e., polysilicon production, wafer manufacturing) for better manufacturing control and cost reductions, and they

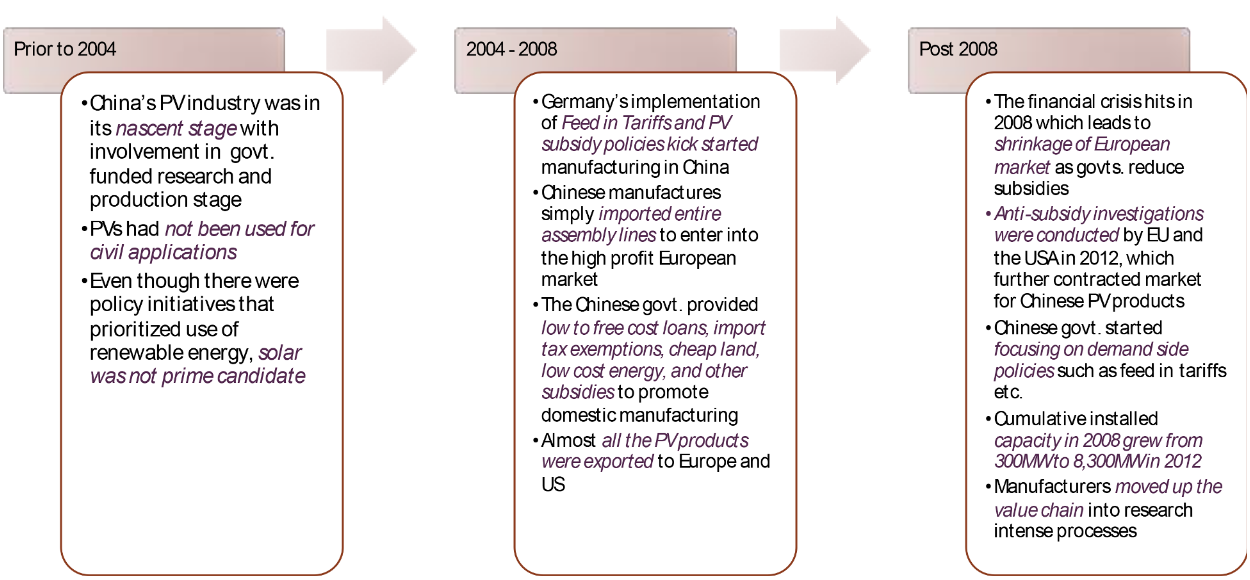

Fig. 6. Development of the Chinese Solar PV Industry

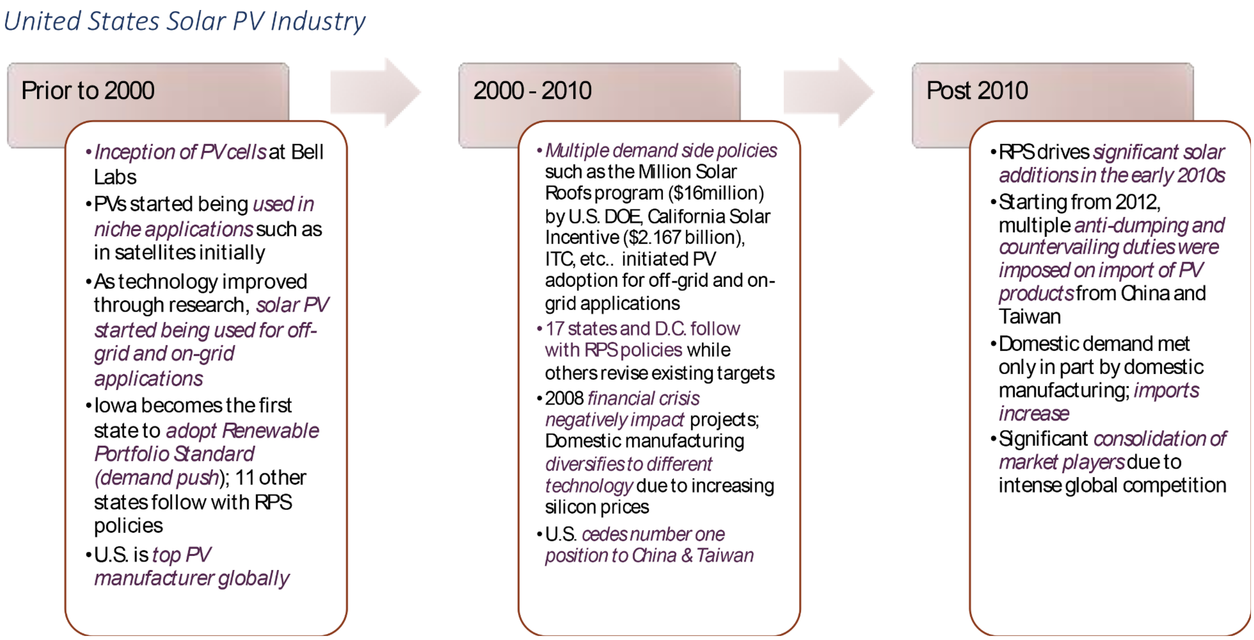

Fig. 7. Development of the United States Solar PV Industry

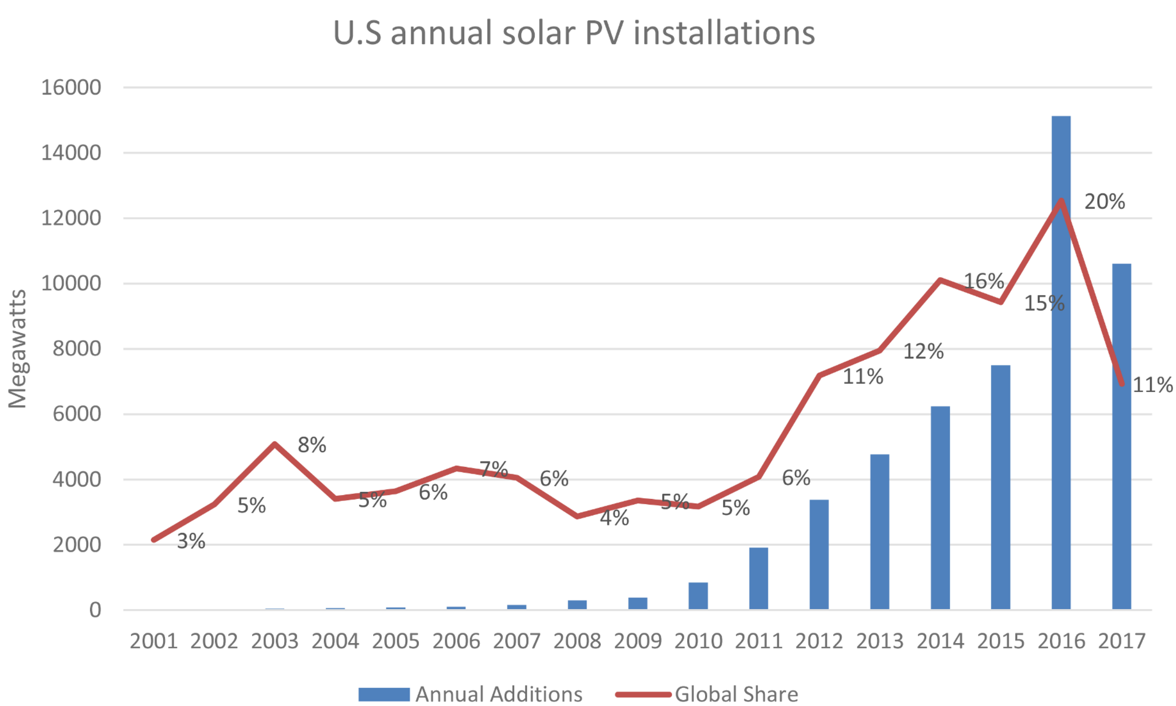

Fig. 8. Annual domestic solar PV installations and global share

been successful in capturing significant market shares.

As of 2019, Chinese module manufacturing accounted for more than 70% of global capacity and remains to be the biggest market for PV installations [29]. Chinese manufacturers have shifted export focus to emerging markets such as India and Mexico even as developed countries such as the United States continue to levy measures to reduce Chinese imports.

United States solar PV industry

This subsection provides an overview of the major developments in the United States Solar PV Industry (Fig. 7). The United States has a long history of research and development of solar PV with one of the notable milestones being the development of the first silicon PV cell at Bell Labs in 1954 [84]. One of the earliest uses of this technology was to power satellites and remains to do so.

Over the next four decades (1960s-1990s), various improvements to solar PV such as efficiency gains, development of newer technologies materials as thin-film solar cells were achieved along with price declines. On the demand side, interest for distributed energy technologies and alternative sources of energy grew primarily as a result of the *Energy Crisis* of the 1970s [84]. Iowa became the first state to adopt a *Renewable Portfolio Standard (RPS)* in 1983 which mandated utilities to procure a certain portion of their energy from alternative energy sources such as solar

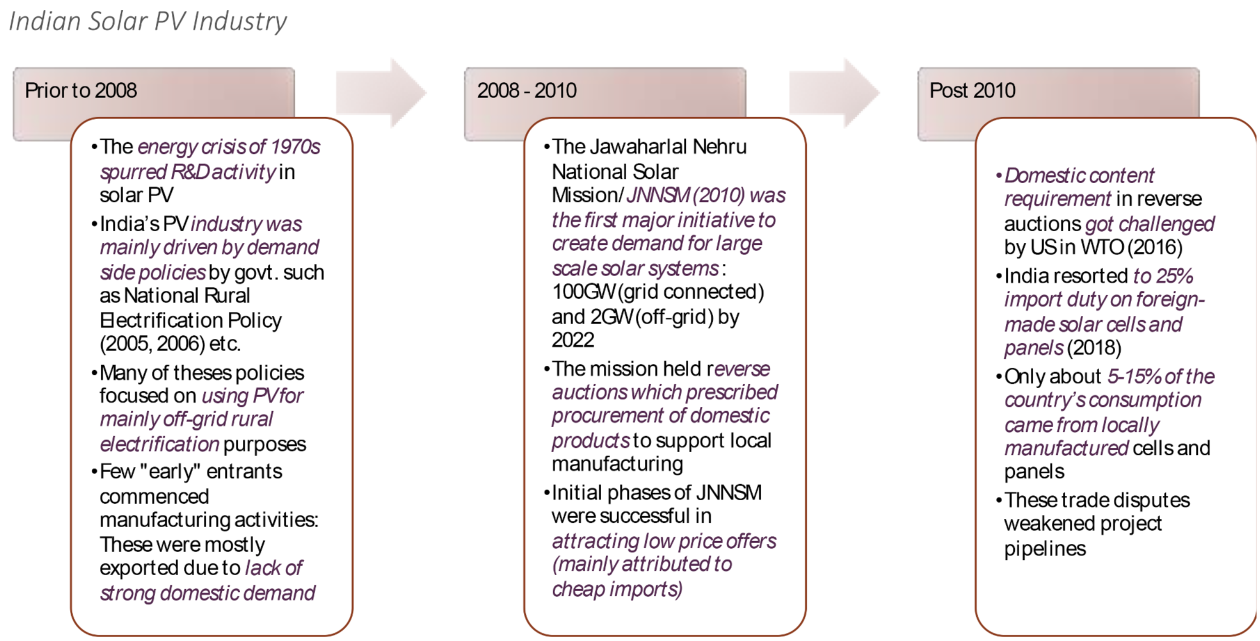

Fig. 9. Development of the Indian Solar PV Industry

PV. 11 other states followed suit in the 1990s to implement such standards. The U.S. also established itself as the top manufacturer of solar PV cells globally [25].

Between the years 2000 and 2010, 17 more states enacted RPS policies while several states revised existing ones. The *Energy Policy Act of 2005* introduced financial incentives such as tax credits for investments in solar energy. Despite this demand-side push, growth in deployment during this period struggled due to the impact on project financing from the 2008 financial crisis [4]. Imports of silicon solar PV modules into the country also increased significantly [57, 78]. The U.S. also ceded its position as top manufacture to China and Taiwan.

Post-2010, domestic solar installations saw a significant increase (Fig. 8) due to utility-scale plant deployments which were mainly driven by RPS targets and financial incentives [3, 56]. This demand was met only partly through domestically manufactured content, however. Imports for solar modules rose significantly from $2GW_{DC}$ in 2010 to $13GW_{DC}$ in 2016. Stiff competition from the international players and falling prices for solar panels had led to significant consolidation in the domestic market, which further reduced the presence of U.S. manufactured products [57].

Presently, the United States accounts for only about 1% of the global solar PV module manufacturing capacity with one company among the top ten manufactures in the world. It is to be noted that U.S. manufacturers have a presence in higher-value processes/segments such as solar factory equipment, and polysilicon manufacturing [57, 80]. But even in these segments, Chinese manufacturers have started to capture significant market shares.

Indian Solar PV Industry

This subsection provides an overview of the major developments in the Indian solar PV Industry (Fig. 9). India realized the need to develop its renewable energy sector with the energy crisis of the 1970s. But the development of the solar PV industry was limited to the involvement of only various public sector companies and government bodies in research, technology commercialization, and manufacturing [61].

The involvement of private entities was limited to small scale commercial manufacturing (under 5MW) starting in 1991. Many of the earlier government policies such as the *National Rural Electrification Policy* were directed to use such technologies for rural electrification and off-grid applications. Up until the conception of the *Jawaharlal Nehru National Solar Mission (JNNSM)* in 2010, India had only about 17 MW of installed solar capacity. Similarly, the module manufacturing capacity in the country was less than half of that in China [60, 65]. Most of this production was export-oriented due to a lack of strong domestic demand.

JNNSM, introduced in 2010 and modified later, was the first major initiative that directly created a significant demand for both utility-scale and off-grid solar (PV and thermal) systems: 100GW of grid-connected & 2GW off-grid by 2022 [61]. JNNSM was successful in being able to increase the installed solar PV capacity to about 22GW in the financial year 2018. Procurements have also seen lower cost than traditional thermal generators in some cases mainly low cost imported solar panels.

Despite the short term domestic content requirement in JNNSM procurements, Indian manufacturing could not compete with cheaper Chinese imports. At least 90% of the solar cells and panels consumed in India between FY 2015 and 2018 have been imported [74, 80]. Nonetheless, Indian manufacturers focused on exports to countries such as the United States [74].

In 2018, the Indian government imposed safeguard duty of 25% on imports to safeguard local manufacturers. The effectiveness of such a measure has been questionable, however, potentially due to the recent stagnation of demand in the market [74]. Presently, domestic manufacturing capacity is significantly less than the projected annual demand of 20GW; however, it plans to expand subjected to continued protection from imports [2, 70].

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