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Has India's Solar Mission increased the deployment of domestically produced solar modules?

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HIGHLIGHTS

- Effectiveness of India's Solar Mission in promoting domestic content is assessed.
- The Solar Mission promoted domestic crystalline silicon modules overall.
- This effect was not as prominent as the DCR was tightened over time.
- Ultimately, the Solar Mission allowed for leakage to foreign thin-film modules.
- To be effective, the DCR would need to be comprehensive across module types.

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ABSTRACT

The Jawaharlal Nehru National Solar Mission (JNNSM), India's flagship policy for solar energy deployment, includes an increasingly strict Domestic Content Requirement (DCR) intended to promote the domestic crystalline photovoltaic solar industry. We examine the impact of the JNNSM DCR on the utilization of domestic and domestic crystalline silicon modules. Using a plant-level database of approximately 250 plants, we show that the first, and weaker, version of the policy accomplished its intention of promoting domestic crystalline silicon modules. However, the second, and stricter, version of the policy has not been as effective: it appears to have promoted the use of foreign thin film modules instead. This analysis shows that the tightening of the DCR was associated with leakage to foreign thin film modules. This suggests that DCR policies need to be comprehensive in scope to ensure that they achieve a goal of using only domestic content; however, policymakers should appropriately assess the welfare impacts of such restrictions.

1. Introduction

1.1. The JNNSM DCR

The Jawaharlal Nehru National Solar Mission (JNNSM)[1] is India's flagship policy on renewable energy (MNRE, 2009). It is part of India's National Action Plan on Climate Change, which focuses on India's response to climate change, and addresses diverse policy issues such as energy security and the creation of new competencies (PMI, 2010).

Among the most prominent of the JNNSM goals is the deployment of 20 GW of utility scale solar power by 2022 using solar photovoltaic (PV) and solar thermal technologies (MNRE, 2009). The JNNSM plans to achieve this target in three phases, with the first targeting 1 GW by 2013, the second 4–10 GW by 2017, and the third 20 GW by 2022. Phase I was further split into two batches. Batch I targeted the deployment of 150 MW of solar PV technology and 500 MW of solar thermal technology, and Batch II targeted the deployment of 350 MW of solar PV technology. As of July 2013, Phase 1 has been completed and Phase 2 is yet to start. In Phase 1, the JNNSM reached approximately 85% of stated targets for solar PV deployment; however, with close to zero capacity online, it appears to have failed to deploy solar thermal technology (Shrimali and Nekkalapudi, 2013).

The JNNSM also seeks to bolster the global competitiveness of the Indian solar manufacturing sector across the value chain (MNRE, 2009). The JNNSM aspires to achieve this goal by promoting research and development, and by ensuring a market for domestic solar manufacturers. To accomplish the latter, the JNNSM includes a controversial but commonly used industrial policy in its Phase 1 policy (Veloso, 2001; Pack and Saggi, 2006): a Domestic

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[1] List of abbreviations: Domestic Content Criteria (DCR); Jawaharlal Nehru National Solar Mission (JNNSM); Photovoltaic (PV)

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Content Requirement (DCR) on both solar PV and solar thermal components.[2] Given the JNNSM's apparent failure to deploy solar thermal capacity (Shrimali and Nekkalapudi, 2013); the focus of this paper is on the former – i.e., the solar PV DCR.

The JNNSM DCR for solar PV is technology-specific and applies only to crystalline silicon modules, with no such restrictions on thin film modules, the other dominant solar PV technology (IRENA, 2012). This specificity reflects that most Indian solar PV manufacturers are focused on crystalline silicon technology. In 2011, the domestic crystalline silicon manufacturing capacity was 1.7 GW, while that for thin film was 200–300 MW (Lux Research, 2012).

The JNNSM Phase 1 DCR is also incremental in nature. In Batch I, the DCR stipulated that all crystalline silicon modules deployed in JNNSM solar plants had to be manufactured in India. Batch II strengthened the DCR by mandating that, in addition to modules, all the crystalline silicon cells in JNNSM solar plants had to be manufactured in India. Other upstream and balance-of-system components could be sourced globally, reflecting the realities of the Indian solar PV manufacturing sector, which is focused on the downstream components of the solar PV value chain (Sahoo and Shrimali, 2013).[3] *In summary*, *the JNNSM DCR has a specific focus of promoting domestic crystalline silicon cells and modules*.

1.2. DCRs: motivations and prior work

DCRs generally attempt to ensure that the deployment of the target technology favors (a) the growth of a globally competitive domestic industry and (b) an increase in economic efficiency (Veloso, 2001; Pack and Saggi, 2006). The DCR is a highly controversial industrial policy since it is illegal under the rules governing world trade (Kuntze and Moerenhout, 2013). Further, though there is evidence that DCRs work in some contexts – e.g., China's wind DCR is credited with contributing to a competitive domestic wind sector (Kuntze and Moerenhout, 2013; Bradsher, 2010), there is considerable ambiguity about whether DCRs generally deliver gains in global competitiveness and economic efficiency (Kuntze and Moerenhout, 2013; Veloso, 2001). For example, Pack and Saggi (2006) argue that industrial policies, and DCRs, in particular, have had at best a limited impact on building competitive domestic industries. Veloso (2001) more positively evaluates DCRs by arguing that negative welfare assessments ignore a gap between social and private valuations of the DCR. In particular, he argues that DCRs can encourage the growth of a network of domestic firms that interact with the protected industry, attract new foreign direct investment, and trigger learning effects.

The record of DCRs has been inconsistent even within the limited context of the renewable energy industry. Kuntze and Moerenhout (2013) examine DCRs for renewable energy technologies across thirteen jurisdictions and observe that the use of these policies appears to be based primarily on political motivations instead of sound economic analysis. However, they find that DCRs may be effective under certain conditions, including: (a) the presence of a stable and sizeable market with predictable investor returns and (b) the realization of local learning benefits in the presence of an appropriate enabling environment. They caution, however, that additional conditions for creating global competitiveness are many, complex, and country- and technology-specific.

This specificity implies that the competitiveness and efficiency impacts of individual DCRs must be empirically evaluated. Previous work suggests that the JNNSM DCR is unlikely to yield a globally competitive domestic solar PV industry (Sahoo and Shrimali, 2013; Johnson, 2013). Sahoo and Shrimali (2013) show that: (a) the Indian PV sector has become less competitive over time, (b) there may be leakage in the JNNSM towards thin film technology, and (c) the Indian innovation system is unlikely to help due to gaps and inefficiencies. Johnson (2013), using an effectiveness framework developed in Kuntze and Moerenhout (2013), supports the findings in Sahoo and Shrimali (2013). Johnson (2013) further asserts that, for the JNNSM DCR to be effective in supporting local employment and private sector development, it must be: (a) limited in duration and evaluated often, (b) focused on technologies for which local expertise is readily available and global market entry barriers are manageable and (c) linked to supporting mechanisms, such as training.

Given this assessment, it is unsurprising that previous work suggests that the JNNSM DCR is unlikely to increase social welfare. It is well-known that, since DCRs restrict the market, in the short-run they would usually increase prices and reduce welfare (Kuntze and Moerenhout, 2013; Sahoo and Shrimali, 2013). Though they may increase welfare in the long-run, they require the existence of a large, stable market, a clear, enforceable, and adaptable policy design, strong financial incentives and industrial sophistication and innovation potential (Veloso, 2001; Kuntze and Moerenhout, 2013). Given these conditions set forth by Kuntze and Moerenhout (2013), Johnson (2013) shows that the JNNSM DCR is unlikely to increase welfare.

1.3. Our work

The overall contribution of the JNNSM DCR to economic efficiency and global competitiveness may only be definitively gauged ex post. However, improvements in either will likely require increased production by Indian manufacturers and deployment of their output. The objective of this paper, therefore, is to examine whether the JNNSM DCR has accomplished the most basic goal of DCRs; namely, has it increased, even within the JNNSM, the deployment of cells and modules produced by the Indian solar PV sector?

In particular, we ask: has the JNNSM DCR (at least) achieved an embedded goal of ensuring that a higher fraction of solar PV plants in the JNNSM use domestic modules?[4] This condition – supporting more domestic modules – is a necessary condition for increasing competitiveness (Kuntze and Moerenhout, 2013), given that it would ensure a secure and stable market for innovation by domestic manufacturers, assuming that the appropriate environment were to be created. Since the JNNSM applies to only crystalline silicon modules, an interpretation of this question is: has the JNNSM DCR resulted in a higher fraction of JNNSM solar PV plants using domestic crystalline silicon modules?

This paper differs from previous work on the JNNSM DCR – i.e., Johnson (2013) and, in particular, Sahoo and Shrimali (2013) – in several major ways. First, earlier work examines technology and sourcing decisions by project developers as part of a larger ex ante framework by which to judge the likely dynamic competitiveness and welfare impacts of the DCR. These ex ante assessments are pessimistic about these outcomes. This paper presents an ex post

[2] The DCR is also known as Local Content Requirement (LCR). For more details on the rationale for DCRs see Pack and Saggi (2006). Further, Veloso (2001) contains an exposition on the effectiveness of DCRs.

[3] The crystalline silicon solar PV value chain consists of the production of the following components, in sequence: polysilicon, wafers, ingots, cells and modules (Sahoo and Shrimali, 2013).

[4] It is important to differentiate between the "fraction" of solar PV plants using domestic solar PV technology and the "volume" of domestic solar PV technology. Though an increased volume could result in the dynamic learning effects, in order to assess the impact of policy, this volume increase has to be appropriately normalized and, therefore, the fraction is an appropriate dependent variable to examine.

analysis and a perspective agnostic to public economics implications but with a goal of understanding whether the policy has achieved a more fundamental goal of increasing the utilization of domestic solar PV cells and modules within JNNSM plants. This increase could, over the long-term, deliver the dynamic gains in competitiveness and welfare that can only be probabilistically assessed ex ante.

Second, we utilize a larger data set that allows us to observe smaller scale plants and those under Batch II of the JNNSM. This plant-level database includes approximately 250 solar PV plants, covering a cumulative solar PV capacity of approximately 1.8 GW. This is approximately equal to the total capacity commissioned in India through June 2013 (MNRE, 2013).[5] The database differs from earlier versions (e.g., in Sahoo and Shrimali (2013)) in its inclusion of plants of capacity lesser than 1 MW; more importantly, it includes information on all the plants in JNNSM Batch II, allowing us to not only derive more nuanced results but also utilize a broader base of comparison in an analysis of trends in technology choice by solar project developers. (Section 2 provides additional details about the database and methods.)

Third, previous analyses implicitly assume that only an expansion in domestic crystalline silicon modules would indicate an effective policy regime. Our treatment is more general in that it tests for an increase in domestic solar modules, regardless of technology. This perspective and the additional variance in JNNSM Batch II technology choice embedded in the larger data set allow us to consider different policy options than those considered in Sahoo and Shrimali (2013). Specifically, the competitiveness and efficiency perspectives in Sahoo and Shrimali (2013) prompted a policy recommendation to abolish the JNNSM DCR. In this paper, we ask whether the JNNSM DCR can at least be justified on the basis of increasing the deployment of output from the Indian PV sector.

Fourth, using a rigorous counterfactual policy, we quantitatively cement earlier suspicions of leakage in Batch II of Phase I of the JNNSM toward foreign thin-film modules.

1.4. Paper organization

The remainder of the paper is organized as follows. In Section 2, we present our methods and describe the data. Section 3 presents results based on aggregate statistics (Section 3.1) and our empirical analysis (Section 3.2); in Section 3.3, we discuss our results. Section 4 concludes by summarizing our work, providing policy implications, and indicating avenues for future work.

2. Methods and data

In this section, we present our methodology (Section 2.1) and describe our data (Section 2.2).

2.1. Methods

Given that we are interested in assessing the effectiveness of the JNNSM DCR in increasing the likelihood that project developers source domestic crystalline silicon modules, we first test the following hypothesis:

[5] Note that our database includes plants for which technology choice was made by October 2012, including plants that are under construction; the official data in MNRE (2013) contains only plants that are commissioned or operational by June 2013.

Hypothesis 1(a). The JNNSM DCR has increased the likelihood that project developers choose domestic crystalline silicon modules.

Despite the fact that the JNNSM DCR targets only crystalline silicon modules, we are also interested in whether it increased the domestic content overall, including both crystalline silicon and thin film modules. Therefore, we also test the following hypothesis:

Hypothesis 1(b). The JNNSM DCR has increased the likelihood that project developers choose domestic modules.

Since the DCR only covers crystalline silicon modules, it is possible that the JNNSM has not achieved these goals; instead, there could have been leakage from crystalline silicon to thin film modules. Thus, we next test the following hypothesis:

Hypothesis 2. The JNNSM DCR has increased the likelihood that project developers choose crystalline silicon modules.

We examine these hypotheses from two angles. First, we assess high-level statistics of technology choice (Section 3.1) to arrive at broad and suggestive observations. Second, we control for various scenarios and parameters and model technology choice using logistic regressions (Section 3.2) to arrive at our final conclusions. We note that both of these assessments are primarily with respect to plants that are outside of the JNNSM stipulations; however, where appropriate, we compare the performance of the two batches against each other.

In the end, we would like to establish how different deployment policies influence technology choice. However, to do so, we need to observe deployment not only under the JNNSM policies but also within a *baseline* policy without the DCR requirement. The latter would provide a counterfactual indicating what technology choice would have been in absence of a DCR. The Gujarat state-level solar policy provides this counterfactual. Thus, the analysis of technology choice in the JNNSM batches is performed relative to the technology choice under the Gujarat policy. All policy variables are used as dummy (or binary) variables – i.e., they are '1' when the policy is active and '0' otherwise.

There are many reasons for selecting the Gujarat policy as the counterfactual (Bridge to India, 2013; Shrimali and Nekkalapudi, 2013). First, as of June 2013, the Gujarat policy, which started a year earlier than JNNSM (i.e., in 2009), registered the installation of approximately 850 MW in capacity. This is in the same order as JNNSM, which recorded approximately 600 MW of installations. Thus, our use of the Gujarat policy as a counterfactual not only ensures a temporal overlap with the JNNSM but also guarantees ample data for empirical analysis under both the counterfactual and JNNSM. Second, and most importantly, the Gujarat policy does not have a DCR and satisfies the primary requirement for a counterfactual to JNNSM. Finally, though the Gujarat policy has included two phases of procurement (in 2009 and in 2011), it has been very stable in terms of underlying parameters and their similarity to those in the JNNSM – in particular, both offer a long-term, fixed-price contract with a credit-worthy counterparty.

We note that, besides policies, many other variables can affect technology choice for solar PV plants. The main one is the size (or capacity) of the solar installation. For example, for rooftop systems, especially in the commercial (generally 10 kW–100 kW) and residential (generally less than 10 kW) sectors, there is very little deployment of thin film (Barbose et al., 2012), primarily due to space constraints on rooftops. Thin film modules have lower efficiencies than crystalline silicon alternatives and, to produce the same amount of power, they require a larger physical footprint (IRENA, 2012). Thus, we control for the capacity of plants in megawatts (MW) in our analysis.

Table 1
Statistics for independent and dependent variables (232 observations).

Variable	Average	Standard deviation	Minimum	Maximum
Crystalline choice	0.59	0.49	0	1
Domestic crystalline choice	0.49	0.50	0	1
Domestic choice	0.56	0.50	0	1
JNNSM-Batch I	0.13	0.33	0	1
JNNSM-Batch II	0.12	0.33	0	1
Gujarat policy	0.26	0.44	0	1
Capacity (in MW)	7.52	10.18	0.01	75

Other potential variables of interest include resource availability and financing mechanisms, but we do not include them in our analysis. In general, the reason for exclusion is that the variation in the excluded independent variables is either limited or is not expected to impact our dependent variable, technology choice (Wooldridge, 2002), as discussed in detail below.

First, though resource variation influences the eventual performance of a plant, it should not influence the choice between crystalline silicon and thin film modules, particularly when land availability is not an issue (Barbose et al., 2012; IRENA, 2012). This is the case for the utility scale plants under both JNNSM and Gujarat policies. Moreover, most of the solar PV plants under the JNNSM are in Rajasthan, and all the plants under the Gujarat policy are in Gujarat (Bridge to India, 2013). The solar insolation in these two states is very similar (SolarGIS, 2013), and is therefore unlikely to visibly impact technology choice in our sample. Further, state-level fixed effects, which may control for resource variation, are likely to be highly correlated with respective policies; specifically, the Rajasthan fixed effect would be highly correlated with the JNNSM dummy and the Gujarat fixed effect with the Gujarat dummy. Therefore, these state-level fixed effects are also not valid instruments for our analysis (Wooldridge, 2002).

Second, financing mechanisms, especially the availability of low-interest loans from the US Export Import (EXIM) Bank to finance the use of modules produced by US manufacturers (Gifford, 2011), would help both crystalline silicon and thin film modules and, given a level playing field, should not influence the choice between the two solar PV technologies. But, given that US crystalline silicon modules are banned under the JNNSM, this low-interest lending applies only to U.S. thin film modules, and financing could influence the technology choice at the plant level. However, we do not include EXIM financing as an independent variable for two reasons. Most importantly, EXIM financing would have an influence on technology choice only because of the policy (e.g., JNNSM) and, therefore, this influence is not independent of the underlying policy. Further, indicative evidence suggests that EXIM financing did not fund many projects and, therefore, should have had a limited impact on technology choice. Our discussions with developers (e.g., SolaireDirect, the lowest bidder in JNNSM Batch II, and Solarsis, a major Indian solar PV developer) indicate that few plants actually used U.S. EXIM lending. This is also supported by the BNEF (2012) database which, though possibly incomplete, indicates that only one out of 123 solar PV plants commissioned in India between March 2012 and May 2013, during which JNNSM Batch II was active, was financed through EXIM lending.

2.2. Data

We started with a plant level database of approximately 250 plants in India, spanning approximately 1.8 GW of solar PV capacity. This database was assembled by combining records from Bloomberg New Energy Finance (BNEF, 2012), Alternative Energy eTrack (eTrack, 2012), and the project design documents for the Clean Development Mechanism (CDM, 2012). We supplemented these records with secondary sources, which primarily include press releases and media coverage.

This plant level database contains plants for which project developers had made a technology choice by October 2012.[6] However, for approximately 20 records, we were unable to determine whether the plant used domestic technology. These entries were excluded from the final analysis, which is thus based on approximately 230 observations. An implication is that our database is not comprehensive, and this may have some implications for our inference, as indicated in Section 3.2.2.

Table 1 provides basic statistics for the independent (i.e., JNNSM-Batch I, JNNSM-Batch II, Gujarat policy and capacity) and dependent variables (i.e., crystalline silicon choice, domestic crystalline silicon choice and domestic choice). As we have mentioned earlier, the policy variables are binary variables and the capacity is a continuous variable. The three choice variables are binary variables. For example, the crystalline silicon choice variable is '1' when the plant chooses crystalline silicon technology and '0' otherwise. A similar codification applies to the domestic crystalline and domestic choice variables.

3. Results and discussion

In Section 3.1, we present preliminary observations based on aggregate statistics; in Section 3.2, we validate these preliminary observations with empirical analyses.

3.1. Results: aggregate statistics

Columns (A) and (B) in Table 2 show the fraction of crystalline silicon and domestic crystalline silicon modules, respectively, under different policies. Both of these are computed as fractions of total capacity deployed in our database and, therefore, the latter is always less than or equal to the former. In the former – i.e., Column (A) – the quantity in the parenthesis indicates the fraction of thin film modules, which is essentially one minus the main – i.e., non-parenthesized – entry.

In Column (C), we have also included the fraction – again, with respect to total capacity – of domestic modules, including domestic crystalline silicon and domestic thin film, with the quantity in parentheses indicating the fraction of domestic thin film modules. That is, the parenthesized entry in the Column (C) is the difference between the non-parenthesized entry in Column (C) and the entry in Column (B).

Finally, note that the non-JNNSM row covers all projects not in the JNNSM, but includes those under the Gujarat policy. Similarly, the non-Gujarat row spans all projects not under the Gujarat policy, but includes the projects under the JNNSM. The impact of

[6] Note that this includes all plants for which a technology choice has been made. These plants are those in one of the following stages: announced, under construction and commissioned.

Table 2
The fraction of crystalline silicon and domestic crystalline silicon modules in plants commissioned under different policies.

Row number	Policy	Fraction of crystalline modules (thin film) (A)	Fraction of domestic crystalline modules (B)	Fraction of domestic modules (thin film) (C)
1	Non-JNNSM	0.66 (0.34)	0.53	0.61 (0.08)
2	JNNSM-Batch I	0.52 (0.48)	0.52	0.52 (0.00)
3	JNNSM-Batch II	0.25 (0.75)	0.25	0.31 (0.06)
4	JNNSM (Batch I+II)	0.39 (0.61)	0.39	0.42 (0.03)
5	Non-Gujarat	0.64 (0.36)	0.58	0.62 (0.04)
6	Gujarat	0.46 (0.54)	0.25	0.39 (0.14)
7	Non-Policy (neither JNNSM nor Gujarat)	0.76 (0.24)	0.67	0.72 (0.05)

either policy would ideally be measured using the non-policy (i.e., neither JNNSM nor Gujarat) row 7. However, in Sections 3.1.1 through 3.1.3, our comparisons of plant technology choice under the JNNSM and Gujarat policy (rows 2–3 and 6, respectively) are with respect to the non-JNNSM and non-Gujarat baselines (rows 1 and 5, respectively). Thus, our observations in the remainder of Section 3.1 are at best suggestive; Section 3.2 presents logistic regressions to rigorously examine these data.

3.1.1. *Fraction of domestic crystalline silicon modules*

Broadly, the data show that, relative to the non-JNNSM (and non-policy) baseline, the fractions of crystalline silicon and domestic crystalline silicon modules have decreased among plants in the JNNSM. Referring to Column (A), the decrease in the share of crystalline silicon modules was more dramatic from the JNNSM Batch I to Batch II (by 0.27 = 0.52–0.25) than it was from the non-JNNSM baseline to JNNSM Batch I (by 0.14 = 0.66–0.52).

Indeed, as the overall share of crystalline silicon modules fell, JNNSM Batch I demonstrated greater domestic crystalline module utilization. Referring to Column (B), there is no perceptible decrease in the fraction of domestic crystalline silicon between the non-JNNSM and JNNSM Batch I (by 0.01 = 0.53–0.52), whereas this fraction drops by 0.27 (= 0.52–0.25) between the JNNSM Batch I and JNNSM Batch II. The higher fraction of domestic crystalline modules in JNNSM Batch I would have been at the expense of thin film (domestic or foreign) or foreign crystalline silicon modules. However, given that both the fractions – i.e., crystalline and domestic crystalline silicon modules – decreased by a similar amount, JNNSM Batch II was not able to support the use of domestic crystalline silicon modules as strongly as JNNSM Batch I.

In contrast, under the Gujarat policy, foreign crystalline silicon modules, whose fraction is given by the difference between the total crystalline silicon module fraction and the domestic crystalline silicon module fraction, were favored at the expense of domestic crystalline silicon modules. Comparing plants in the non-Gujarat policy baseline to those under the Gujarat policy in Table 2, we find that the fraction of domestic crystalline silicon modules has fallen more sharply than has the fraction of crystalline silicon modules (decreases of 0.33 vs. 0.18, respectively).

The observations that the share of domestic crystalline modules dropped more drastically across plants in the Gujarat policy than those under in the JNNSM Batch I (decreases of 0.33 and 0.01, respectively) indicates that JNNSM Batch I achieved its goal of promoting domestic crystalline silicon modules. Further, though the fraction of crystalline silicon has fallen under JNNSM Batch I, this reduction is less than that observed in the Gujarat policy (decreases of 0.14 vs. 0.18, respectively), indicating that JNNSM Batch I DCR somewhat increased the use of crystalline silicon modules compared to the counterfactual.

However, the results are different for JNNSM Batch II, where the fraction of domestic crystalline silicon is about the same as the corresponding fraction for Gujarat policy (i.e., 0.25). Compared to the respective non-policy baselines, the reduction in the fraction of domestic crystalline silicon modules in JNNSM Batch II is less than it is for plants under the Gujarat policy (decreases of 0.28 vs. 0.33, respectively). Since the reduction in crystalline silicon modules in JNNSM Batch II is more than that in the Gujarat policy (decreases of 0.41 vs. 0.18, respectively), the JNNSM Batch II appears somewhat successful in promoting domestic crystalline silicon modules despite actually discouraging the use of crystalline silicon modules.

3.1.2. *Fraction of domestic modules*

Per Column (C), the fraction of domestic modules has decreased among plants in the JNNSM relative to the non-JNNSM baseline (by 0.09 and 0.30 for Batch I and Batch II, respectively). Further, though the fraction of domestic thin film modules fell to zero from the non-JNNSM baseline to JNNSM Batch I, it increased to 0.06 from JNNSM Batch I to JNNSM Batch II. Ultimately, the fraction of thin film in JNNSM Batch II is about the same as the non-JNNSM baseline (0.06 vs. 0.08, respectively), indicating that though the JNNSM appears to have promoted the domestic crystalline silicon module utilization, it has not influenced the utilization of domestic thin film modules.

Compared to the Gujarat policy, JNNSM Batch I not only supported more domestic content (with technology shares of 0.39 vs. 0.52, respectively) but also displayed a smaller reduction in the fraction utilized (decreases of 0.23 vs. 0.09, respectively) relative to the respective baselines, indicating that the JNNSM Batch I DCR was effective in supporting domestic content compared to the counterfactual. However, JNNSM Batch II includes slightly lower domestic content than the Gujarat policy (0.31 vs. 0.39, respectively), indicating that JNNSM Batch II was not as effective in supporting domestic content overall. We also observe that the Gujarat policy, which does not have any form of DCR, includes more domestic thin film modules than JNNSM (overall, 0.14 vs. 0.03, respectively).

3.1.3. *Summary of aggregate statistics results*

To summarize, examining our hypotheses, we have the following preliminary observations:

- ***Observation** 1* **(*a*):** JNNSM Batch I increased the likelihood that project developers chose domestic crystalline silicon modules. JNNSM Batch II, on the other hand, only somewhat increased this likelihood.
- ***Observation** 1* **(*b*):** JNNSM Batch I increased the likelihood that project developers chose domestic modules. JNNSM Batch II, on the other hand, only somewhat decreased this likelihood.
- ***Observation** 2*: JNNSM Batch I only somewhat increased the likelihood that project developers chose crystalline silicon modules. JNNSM Batch II, on the other hand, decreased this likelihood.

Table 3
Logistic regression results for crystalline silicon choice.

Variable	(1)	(2)	(3)
JNNSM-Batch I	0.35**	0.34**	0.44*
JNNSM-Batch II	0.12***	0.16***	0.19**
Gujarat	0.29***	0.34***	0.42**
Capacity		0.96**	0.97**
Pseudo R-squared	0.10	0.12	0.09

Specification (1): All policies; Specification (2): All policies and capacity; Specification (3): All policies and capacity, with capacity restriction (> =1 MW).
* Significant at 10%, ** significant at 5%, and *** significant at 1%. The parenthetical quantity under Specification (3) is the p-value of the coefficient estimate.

Table 4
Logistic regression results for domestic-crystalline silicon choice.

Variable	(1)	(2)	(3)
JNNSM-Batch I	0.54 (0.14)	0.55 (0.16)	0.72 (0.45)
JNNSM-Batch II	0.18***	0.38*	0.45 (0.13)
Gujarat	0.17***	0.23***	0.29***
Capacity		0.92***	0.93***
Pseudo R-squared	0.10	0.17	0.12

Specification (1): All policies; Specification (2): All policies and capacity; Specification (3): All policies and capacity, with capacity restriction (> =1 MW).
* Significant at 10%, ** significant at 5%, and *** significant at 1%. The parenthetical quantity under Specification (3) is the p-value of the coefficient estimate.

Note that these observations are based on the comparison of summary data and should be interpreted as suggestive. These are further examined and strengthened in Section 3.2.

3.2. Results: empirical analysis

The observations made in Section 3.1.3 are suggestive, given that they are based on aggregate statistics, are relative to the non-JNNSM/non-Gujarat cases as opposed to the non-policy one, and do not control for many confounding variables. We now examine these high-level observations in more detail, using logistic regression analysis (Wooldridge, 2002). This analysis models technology choice as the dependent variable, using crystalline silicon module selection in one case and domestic crystalline silicon module selection in another. In a third case, it uses overall domestic module selection as the dependent variable. The logistic regression coefficients are odds-ratios, which are proxies for the probability (or fraction) of the corresponding dependent variable chosen.[7]

We use the following specifications (Table 3–5). Specification (1) represents a regression with only policy dummies – i.e., those for the JNNSM Batch I, JNNSM Batch II and Gujarat policies. We use two different variables for JNNSM Phase 1 – one for each batch – to ensure that we capture the impact of each version of JNNSM DCR separately. Specification (2) adds the capacity of installation to Specification (1). This distinguishes module choice decisions that are capacity-dependent from those that are policy-dependent. Finally, Specification (3) adds a capacity restriction to Specification (2); it examines installations greater than or equal to 1 MW in capacity. This is done to focus on the utility-scale capacities where these policies were applicable (Barbose et al., 2012). We therefore

[7] The odds-ratio is defined as $p/(1\text{-}p)$, where "p" is the probability of the event we are interested in (e.g., probability of crystalline module being selected). Thus, the odds-ratio is 0 when $p=0$; 1 when $p=0.5$; and infinity when $p=1$.

Table 5
Logistic regression results for domestic choice.

Variable	(1)	(2)	(3)
JNNSM-Batch I	0.42**	0.41**	0.53 (0.14)
JNNSM-Batch II	0.20***	0.32**	0.38**
Gujarat	0.26***	0.32***	0.40***
Capacity		0.95***	0.96***
Pseudo R-squared	0.08	0.12	0.08

Specification (1): All policies; Specification (2): All policies and capacity; Specification (3): All policies and capacity, with capacity restriction (> =1 MW).
* Significant at 10%, ** significant at 5%, and *** significant at 1%. The parenthetical quantity under Specification (3) is the p-value of the coefficient estimate.

consider Specification (3) to be the most complete specification for drawing inferences.

3.2.1. Choice of crystalline silicon modules

Table 3 shows the logistic regression results for the choice of crystalline silicon modules. In all three specifications, all of the policy variables are statistically significant and, in the two specifications in which it is included, so is the capacity variable.[8] In what follows, we focus on the most complete specification, Specification (3).

Compared to the JNNSM policies, we observe that the odds-ratio of crystalline silicon module utilization in the Gujarat policy, which does not have the DCR criteria, is either approximately equal to or more than the corresponding ratios for the JNNSM policies. In particular, we note that JNNSM Batch I plants have approximately the same odds-ratio for crystalline silicon modules compared to those in the Gujarat policy (0.44 vs. 0.42, respectively), and plants in the JNNSM Batch II have a much lower odds-ratio for crystalline silicon modules compared to those in the Gujarat policy (0.19 vs. 0.42, respectively).

This leads to the conclusions that: (a) the initial DCR restriction in the first batch of the JNNSM, compared to the Gujarat policy, did not affect the choice of crystalline silicon modules and (b) the increasing DCR restrictions in the second batch of the JNNSM, compared to the Gujarat policy, have contributed to a shift by project developers away from crystalline silicon modules. This indicates that the incremental DCR restriction of JNNSM Batch II, which includes cells in addition to modules, had a much bigger impact than the incremental DCR restriction of JNNSM Batch I, which includes only modules.

3.2.2. Choice of domestic crystalline silicon modules

We next examine (in Table 4) the logistic regression results for the choice of domestic crystalline modules. Where applicable, the quantities in parentheses represent the probability (or p-value) that the coefficient on the relevant variable is attributable to random chance, given the null hypothesis that the coefficient is zero (Wooldridge, 2002).

We now run into an issue with statistical significance, however. In Specifications (2) and (3), many of the JNNSM variables – in particular, Batch I – are not statistically significant within a 10% criterion. The Gujarat policy variable and the capacity variables remain statistically significant. We believe that this is an issue related to the size of our dataset, as indicated earlier (Section 2.2). Notwithstanding the issue of statistical significance, a couple of observations can be made.

[8] Given the small dataset, beyond the traditional thresholds of 1% and 5% (Fischer, 1925), we include the 10% level to identify moderately statistically significant impacts. It is also important to note that we are verifying multiple hypotheses from the data and a correction (e.g., Bonferroni) may be required.

First, compared to Table 3, we observe that under the counterfactual Gujarat policy, the odds-ratio of domestic crystalline silicon module selection remains statistically significant and is less than that for crystalline silicon modules (0.29 vs. 0.42, respectively). This indicates that, in the absence of a DCR, for a project of average capacity, project developers in the JNNSM would have sourced a moderate amount of their crystalline silicon modules from foreign manufacturers. We thus infer that the JNNSM DCR, by completely banning foreign crystalline modules, has driven at least some project developers to source domestic crystalline modules instead of the foreign analogs deployed by their counterparts under the Gujarat policy.

Second, though the coefficients in the domestic crystalline silicon model on JNNSM Batch I and Batch II are not statistically significant, an issue that may stem from the inherent capacity constraint on the number of projects within either the JNNSM Batch I or Batch II, we offer an interpretation that incorporates the point estimates on the effects. For the rest of this sub-section (i.e., in Section 3.2.2), we focus on Specification (2) for two reasons: first, Specification (2) not only has the best fit based on adjusted R-squared but also, given the p-values, offers more confidence in the point estimates than does Specification (3); second and more importantly, the coefficient estimates in Specification (2) appear reasonably close to ones predicted by Specification (3).

Combining the two sets of empirical results on the choice of crystalline silicon (from Section 3.2.1) and domestic crystalline silicon (from Section 3.2.2), we can make the following deductions. First, the JNNSM DCR, by banning foreign crystalline silicon modules only (i.e., in Batch I), increased the share of domestic crystalline silicon modules compared to a counterfactual policy, such as Gujarat. This follows from the observation that the odds-ratio of domestic crystalline silicon choice in the Gujarat policy is much lower than the odds-ratio of domestic crystalline silicon choice for JNNSM Batch I (in Specification (2), 0.23 vs. 0.55, respectively). Moreover, while the odds-ratio of the Gujarat policy decreases from the model of crystalline choice (Table 3) to that of domestic crystalline choice (Table 4), the odds-ratio of the JNNSM Batch I policy increases across models. Thus, it appears that developers in the JNNSM Batch I chose domestic crystalline silicon modules in place of foreign crystalline silicon modules, without thin film modules – domestic or foreign – benefitting much.

Second, though the JNNSM Batch II DCR increased the share of domestic crystalline silicon modules by banning both foreign crystalline silicon cells and modules, the subsequent increase in domestic crystalline silicon module utilization was not as large as that observed from the JNNSM Batch I DCR. This follows from the observation that the odds-ratio of domestic crystalline silicon choice in the Gujarat policy is smaller than the odds-ratio of domestic crystalline silicon choice for JNNSM Batch II (0.23 vs. 0.38, respectively), which itself is lower than the odds-ratio of domestic crystalline silicon choice for JNNSM Batch I (0.38 vs. 0.55, respectively). Thus, in JNNSM Batch II, it appears that in many cases thin film modules were chosen in place of foreign crystalline silicon modules, with the domestic crystalline silicon modules not benefitting as much as they did under JNNSM Batch I.

3.2.3. *Choice of domestic modules*

We examine in Table 5 the logistic regression results for the choice of domestic modules.

We again observe a statistically insignificant term on the JNNSM Batch I coefficient in Specification (3), but we are again limited by the fixed number of JNNSM plants. Compared to the baseline Gujarat policy, it appears that JNNSM Batch I has supported more domestic content (odd-ratios of 0.40 vs. 0.53, respectively). However, this support effectively vanishes in JNNSM Batch II (odds-ratios of 0.40 vs. 0.38, respectively). This finding is consistent with the more nuanced findings in Section 3.2.2.

3.2.4. *Summary of empirical results*

Examining our hypotheses, we summarize the following results that build on the preliminary observations in Section 3.1:

- ***Result*** 1 **(*a*):** JNNSM Batch I increased the likelihood of domestic crystalline silicon module utilization. JNNSM Batch II also increased this likelihood, but by a smaller magnitude.
- ***Result*** 1 **(*b*)**: JNNSM Batch I increased the likelihood of domestic module utilization. JNNSM Batch II, on the other hand, did not change this likelihood.
- ***Result*** 2: JNNSM Batch I did not change the likelihood of crystalline silicon module utilization. JNNSM Batch II, on the other hand, decreased this likelihood.

Thus, we see that the following observations based on aggregate statistics (Section 3.1) did not change: JNNSM Batch I increased the likelihood of domestic (crystalline silicon or total) module utilization and JNNSM Batch II decreased the likelihood of crystalline silicon modules deployment. However, the earlier tentative observations based on aggregate statistics (Section 3.1) can be strengthened to the following: JNNSM Batch I did not change the likelihood of crystalline silicon module selection, and JNNSM Batch II (a) increased the likelihood of domestic crystalline silicon module utilization and (b) did not change the likelihood of overall domestic module use.

3.3. *Discussion*

In this section, we use the results in Section 3.2.4 to arrive at our main conclusions and discuss the reasons behind them. Our analysis shows that both batches in JNNSM supported domestic crystalline silicon module utilization; however, the impact of Batch II was lower than that of Batch I. It also shows that though JNNSM Batch I supported crystalline silicon utilization overall, JNNSM Batch II did not.

The first (and weaker) version of the policy, JNNSM Batch I, achieved its intended goals: it promoted domestic crystalline silicon module uptake (Result 1(a)) and, by keeping the likelihood of project developers choosing crystalline silicon modules the same (Result 2), ensured that these domestic crystalline silicon modules replaced foreign crystalline silicon modules. That is, it promoted the use of domestic crystalline silicon technology in place of foreign crystalline silicon technology.[9] This also ensured that the likelihood of developers using domestic technology increased overall (Result 1(b)), and this was primarily driven by the increased utilization by project developers of domestic crystalline silicon technology.

Though the second (and stricter) version of the policy, JNNSM Batch II, achieved its intended goals, the impact was much lower. It actually reduced the likelihood of project developers choosing crystalline silicon modules (Result 2) and, though it increased the likelihood of domestic crystalline silicon modules (Result 1(a)), this increase was not as pronounced as it was in JNNSM Batch I.

That is, the stricter version of the policy appears to have promoted the use of thin film technology, given that it reduced the likelihood of crystalline silicon technology (Result 2). Thin film modules would have replaced foreign crystalline silicon

[9] This differs from our finding in Sahoo and Shrimali (2013). In this paper, we have enlarged our sample size to include plants with under 5 MW of capacity; the different sample set can explain the discrepancy between our findings in the two papers.

technology, given that the Batch II policy increased the likelihood of domestic crystalline modules while simultaneously reducing the likelihood of crystalline modules (from Results 1(a) and 2). Further, since the likelihood of domestic module choice did not change under JNNSM Batch II (Result 1(b)), and the likelihood of domestic thin film modules decreased (Result 1(a)), it appears that the leakage has been towards foreign thin film modules at the expense of domestic thin film modules.

This analysis demonstrates a potential flaw in the JNNSM DCR policy design that is somewhat obvious in hindsight: while aiming to increase the share of domestic crystalline silicon modules, Indian policymakers inadvertently allowed for leakage to foreign thin film modules. Though the threat of leakage to foreign thin film modules existed in both batches, this became highly visible when the DCR requirements were tightened from Batch I to Batch II of Phase I.

This may have occurred for a few reasons. The first reason is that the quality adjusted prices for domestic crystalline silicon modules using domestic cells were higher than those for domestic modules using foreign cells; the second is that there was not enough domestic cell production capacity. The latter is fairly straightforward and unlikely: both cell and module domestic manufacturing capacities are estimated to be 2.2–2.3 GW per annum (Lux Research, 2012), much higher than the combined goal of 500 MW in the two batches of JNNSM Phase 1. The former takes a bit of reasoning, as follows.

Given that JNNSM Batch I DCR, which allowed foreign cells, increased the likelihood of domestic crystalline silicon module utilization, while the JNNSM Batch II DCR, which precluded foreign cells, increased this likelihood by a smaller magnitude, JNNSM Batch II DCR reduced the price competitiveness of crystalline silicon modules eventually produced. The relatively uncompetitive nature of Indian cell manufacturing is corroborated by capacity utilization figures. Sahoo and Shrimali (2013) present evidence that while Indian module capacity utilization (46% in Q1 2012) is approximately equal to global module capacity utilization (53% in Q1 2012); Indian cell capacity utilization (37% in Q1 2012) is sharply lower than the global figure (57% in Q1 2012). While it is not obvious why these utilization figures differ, cell manufacturing is the more technologically complex step.

4. Conclusions and policy implications

The JNNSM is India's flagship policy for deploying solar energy and includes a DCR to promote the domestic crystalline silicon industry and attempt to make it more competitive in the process. In this paper, we examine the impact of the JNNSM DCR on the choice of crystalline silicon and domestic crystalline silicon modules.

Using a plant level database of approximately 250 plants that represents approximately 1.8 GW of solar PV capacity in India, we show the following. First, though JNNSM Batch I did not change the likelihood of project developers choosing crystalline silicon modules, it increased the likelihood of project developers choosing domestic crystalline silicon modules. Second, though JNNSM Batch II decreased the likelihood of project developers choosing crystalline silicon modules, it increased the likelihood of project developers choosing domestic crystalline silicon modules, but by a smaller degree than JNNSM Batch I.

Our analysis indicates that, as the DCR restriction tightened, there was a leakage to foreign thin-film modules. Thus, if the policy goal were to ensure a higher uptake of domestic modules, regardless of technology, in order to protect the domestic industry and increase its long run competitiveness, the DCR would have to be across both solar PV technologies; that is, it would have to cover both crystalline silicon and thin film modules. We have provided conclusive evidence in support of this suggestion via rigorous analysis.

The reason, as we discuss in Section 3.3, may be that domestic crystalline silicon modules remained price competitive when foreign crystalline silicon cells were allowed (in JNNSM Batch I), but lost this competitiveness as domestic crystalline silicon module manufacturers were forced to use domestic crystalline silicon cells (in JNNSM Batch II). This hypothesis of decreased price competitiveness remains untested as we do not have the price data to test it. Nonetheless, if it is true, it implies that domestic cell manufacturers did not realize adequate cost reductions during the JNNSM Batch I to become globally competitive by the time of the JNNSM Batch II. Thus, although the DCR may be able to expand *module* manufacturing and unleash dynamic learning effects among domestic module manufacturers, it may be unable to expand *cell* manufacturing and increase the competitiveness of domestic cell manufacturers. As we noted, cell manufacturing is the more complex step, and the realization of competitive upstream technologies may require more than the DCR can deliver. Of course, the expansion of the DCR to cover cells in Batch II may initiate technological learning among domestic cell manufacturers. However, as discussed in Sahoo and Shrimali (2013) from a national innovation system perspective, cost competitiveness across the solar value chain will require supplemental improvements in institutional structure, research and development and the establishment of technological linkages across the domestic solar value chain.

While considering a tightening of the DCR restriction to include thin-film modules in addition to crystalline silicon modules, policymakers need to consider the tension between the benefits and costs of DCRs (Veloso, 2001; Kuntze and Moerenhout, 2013). The stringency of an expanded DCR may need to be gradually phased in by allowing some part of the market to be supplied by only domestic manufacturers and the rest open to global competition (Lewis and Wiser, 2007), thus allowing room for experimentation and discovery of the optimal DCR level (Veloso, 2001). This matches current thinking in policy circles in India, particularly with respect to Phase 2 of the JNNSM (MNRE, 2012).[10]

However, ensuring a higher uptake of domestic modules is not a sufficient condition for ensuring long-term competitiveness of the domestic Indian solar PV industry. This, when coupled with the sizable solar PV market under JNNSM, is only one of the necessary conditions (Kuntze and Moerenhout, 2013). In order for the DCR to be effective in the medium- to long-term, it is also necessary for the supporting environment, including innovation potential (Johnson, 2013), to exist. As Sahoo and Shrimali (2013) show, this supporting environment is lacking in India. Thus, if a policy goal were to ensure an effective JNNSM DCR, policymakers should combine a more comprehensive DCR with policies that improve the supporting environment.

We note that our analysis can be improved on many fronts. First, the database needs to be expanded not only to include more plants but also to capture the technology choice of the missing 20 entries (Section 2.2). Our statistical power is limited by the inherent small size of our data set and the discrete nature of solar module technology choice.[11]

Second, Batch I of Phase 2 of the JNNSM, which targets an additional 750 MW of grid connected solar PV installations, will

[10] The latest draft of the policy, released on May 9, 2013, actually discusses two different tranches for the 750 MW of solar PV to be deployed in the first batch of Phase 2 (Solarbuzz, 2013). The first tranche, totaling 250MW of capacity has a comprehensive DCR, including both crystalline and thin film modules; whereas the second tranche, totaling 500 MW of capacity does not have a DCR.

[11] In particular, our methodology does not weigh technology choice by the size of the solar PV plant.

likely include two branches of equal size, with the DCR applicable to only one of them. This design offers a natural experiment from which the causal role of the DCR in driving technology choice can be estimated, and we suggest that researchers continue to assess the impact of the DCR with technology choice data from Phase 2 of the JNNSM.

Third, our analysis could be further strengthened upon including other control variables that may impact technology choice (Section 2.1). One such variable is insolation, which may influence technology choice, particularly when land availability becomes an issue (Barbose et al., 2012; IRENA, 2012). Another variable may be financing, given that the U.S. EXIM bank may have influenced technology choice by providing low-interest loans (Gifford, 2011). We believe that though these variables may not have a first order impact (see discussion in Section 2.1), their inclusion will improve our choice models.

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