Solarization of irrigation in India

An evaluation of policy performance

Thesis Draft

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Preface

Dear Reader,

This master's thesis represents the culmination of my journey through the Master of Science program in Sustainable Energy Technology (SET) at the Technical University of Delft. Reflecting on this transformative experience, I recognize it has been filled with invaluable learnings, significant challenges, and moments of personal and academic growth. This thesis is no exception—it has provided me with the opportunity to explore complex issues, overcome obstacles, and contribute meaningfully to the field of sustainable energy.

The completion of this thesis and my master's program would not have been possible without the support and guidance of numerous individuals and institutions. First and foremost, I express my sincere gratitude to the Technical University of Delft for offering a stimulating environment to learn, experiment, and grow. The opportunity to engage with brilliant minds has profoundly shaped my academic journey. I am also deeply thankful to the professors, PhD researchers, and support staff who have shared their invaluable insights into sustainable energy, fostering my development both professionally and personally.

I owe special thanks to my daily supervisor, Dr. Nihit Goyal, whose constant support and guidance throughout the thesis process were instrumental to its success. His mentorship led me to explore this fascinating topic and navigate the challenges with confidence. I am also deeply grateful to the chairperson of my thesis committee, Dr. Linda Kamp, for her trust in my research proposal and for her critical feedback, which significantly enriched the quality of my work. I extend my gratitude to Dr. Kaveri Iychettira, whose constructive suggestions were particularly helpful during the preparation and execution of interviews. My heartfelt appreciation goes out to the interview participants for their valuable time, enthusiasm, and insights, which added depth and relevance to this research.

I am incredibly fortunate to have been surrounded by friends, both in the Netherlands and back home, who have offered unwavering support throughout this journey. Their kindness, encouragement, and belief in me have helped me navigate challenges and inspired me to grow in every aspect of my life.

I am eternally grateful to my family for their unconditional love and steadfast support. My mother has been my unwavering pillar of strength, always there to guide me and stand by me through every challenge. As I write this, I also want to honor my late father, whose influence and guidance have shaped me into the person I am today. I carry his memory with me, and I know he is watching over me with pride.

As I conclude this note, I am filled with gratitude for all the lessons learned during my master's program and through this thesis. I look forward with anticipation and enthusiasm for the opportunities and challenges that lie ahead in the journey of life.

Aditya Devarajan
Delft, December 2024

Summary

The agricultural sector in developing nations, notably exemplified by India, stands as a significant contributor to greenhouse gas (GHG) emissions, a challenge intensified by India's growing population, which increases demands on agricultural infrastructure. Efforts to boost food production have led to a commensurate escalation in production intensity and output volume, resulting in higher GHG emissions, primarily from fossil fuel use for agricultural inputs. A prominent example of this is the use of diesel-powered irrigation pumps, which account for approximately 28% of irrigation pumps in India, contributing to around 15.4 million tonnes of CO_2 emissions annually.

To mitigate GHG emissions and provide a reliable daytime electricity supply to farmers to power the irrigation, the Government of India launched the *Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan* (PM KUSUM) scheme in 2019. Leveraging India's abundant solar resources, the scheme incentivizes the transition from conventional diesel and electric pumps to solar-powered alternatives. This shift aimed to reduce the long-term subsidy burden on the state while encouraging farmers to adopt solar energy, with the potential for additional income through the sale of surplus electricity. The PM-KUSUM scheme supports both grid-connected and off-grid solar installations for irrigation, aligning with India's national solar mission and reflecting a strategic commitment to clean, sustainable energy sources.

The scheme comprises three components: Component A, for establishing decentralized solar power plants on agricultural land; Component B, for replacing diesel pumps with standalone solar pumps for irrigation; and Component C, for solarizing existing electric grid connected pumps through either individual pump solarization (IPS) or feeder level solarization (FLS)(Rahman et al., 2021). The central government allocated funds for state-level execution, allowing states to adopt components based on local demand. The collaboration between central and state governments is crucial for implementation. While Components A and C have seen limited uptake, Component B has achieved significant solar pump installations. However, there are notable disparities in adoption rates under Component B in different regions, indicating potential differences in policy efficacy across states. While the PM KUSUM scheme represents progress toward solar energy adoption, it also highlights the need to address adoption disparities within the agricultural sector across Indian states.

Despite some academic discussions addressing state-level policy variations, limited attention has been given to the causal complexity and combined effects of factors influencing policy outcomes for agricultural solarization. Most of the studies addressing such a policy also are ex-ante in nature hence they cant account for disparities of performance of the policy in differing contexts. This thesis seeks to illuminate the reasons for the disparities observed in policy performance for solarization of irrigation. To explore how varying factors impact state-level solar adoption, a mixed-methods approach was used. Initially, key factors contributing to higher solar adoption rates were identified through a literature review encompassing social, economic, agricultural, energy, and institutional domains. In the first stage, quantifiable factors were analyzed using Qualitative Comparative Analysis (QCA) to identify causal links, highlighting pathways leading to both positive and negative policy performance outcomes. This analysis also identified factors that synergistically contribute to adoption outcomes.

A detailed scrutiny is devoted to understanding the results of the QCA and providing further information on the outcomes observed. This was accomplished through data collected from semi-structured interviews with key experts who can offer insights into the policy. The interview questions were derived partly from the QCA results and partly from relevant literature, ensuring a comprehensive approach to capturing the nuanced factors influencing policy outcomes. These interviews then were analyzed using thematic analysis to identify recurring themes that emerge during the discussions, further enhancing the understanding of the qualitative comparative analysis results. The analysis also informs about the influence of implementation, coordination of agencies, and the roles of various stakeholders, as these

factors seem not to have variables that can fully capture their influence on policy outcomes across states which could have been effectively incorporated in the QCA. The findings from both QCA and qualitative analyses were synthesized to develop a comprehensive understanding of the underlying factors contributing to variations in solar installation uptake across states under the policy.

Findings indicate that adoption disparities under Component B were shaped by demand, often driven by high water needs or unreliable electricity access, which leads to diesel pump usage and consequently, demand for solar water pumps. However, this demand alone does not ensure successful adoption. Positive policy performance requires that the demand be supported by political commitment or economic resources, whether at the farmer or state level. Additional factors—such as institutional capacity, inter-departmental coordination, and stakeholder involvement, including credit access and vendor support—further enhance the adoption environment. These findings underscore that irrigation demand, when bolstered by political support or economic resources, is essential for meaningful success under the PM KUSUM scheme.

Based on the findings of the thesis the following policy recommendations were made: To improve Component B performance in different regions, the national government should consider extending central financial assistance to under-resourced states, potentially covering parts of the state subsidy component. Improvement of credit access, facilitated by partnerships with financial institutions and expanded online platforms, would reduce financial barriers for farmers. Addressing institutional bottlenecks within implementing agencies would also improve efficiency of deployment. Collaborative purchasing among states could further optimize adoption, particularly in regions with low demand.

Future research could explore policy deployment across energy and agriculture intersections, assess comparable policies for shared insights, and examine farmer-level adoption behaviors across regions. Additionally, focusing on long-term environmental impacts, such as groundwater sustainability, and monitoring policy outcomes over time would provide valuable insights into the performance of a policy at the energy-agriculture nexus, like PM KUSUM.

Contents

Preface i

Summary ii

Nomenclature ix

1 Introduction 1
- 1.1 Background . . . 1
- 1.2 Research gap and objective . . . 5
- 1.3 Main research question and sub questions . . . 6
- 1.4 Relevance of Thesis . . . 6
- 1.5 Outline of thesis . . . 6

2 About the Policy: PM KUSUM 8
- 2.1 Background . . . 8
- 2.2 PM KUSUM . . . 10
- 2.3 Salient features of PM KUSUM . . . 11

3 Factors which can influence solar adoption in agriculture 13
- 3.1 Socio-economic . . . 16
- 3.2 Energy . . . 16
- 3.3 Agricultural . . . 16
- 3.4 Policy related factors which could influence outcomes . . . 17

4 Research Methodology 18
- 4.1 Research Approach . . . 18
- 4.2 Qualitative comparative analysis(QCA) . . . 20
  - 4.2.1 Types of QCA . . . 20
  - 4.2.2 Limitations of fsQCA . . . 21
  - 4.2.3 FsQCA application . . . 21
  - 4.2.4 Dependent Variable - Outcomes of PM KUSUM scheme . . . 24
  - 4.2.5 Causal conditions - Factors which influence outcomes . . . 24
  - 4.2.6 Operationalization of Dependent Variables . . . 27
  - 4.2.7 Operationalization of causal conditions . . . 28
  - 4.2.8 Validity and Reliability . . . 31
- 4.3 Qualitative Analysis . . . 32
  - 4.3.1 Semi-structured interview . . . 32
  - 4.3.2 Expert Pool Selection and Interview Process . . . 32
  - 4.3.3 Interview outline . . . 33
  - 4.3.4 Thematic analysis . . . 33
  - 4.3.5 Limitations of semi-structured interviews and thematic analysis . . . 34

5 Results of QCA and Thematic Analysis 35
- 5.1 Raw datasets, calibrated datasets and types of solutions of fsQCA . . . 35
- 5.2 Thematic analysis development . . . 37
- 5.3 Results of fsQCA and thematic analysis . . . 38
  - 5.3.1 Results of the QCA for positive outcomes of component B of PM KUSUM . . . 39
  - 5.3.2 Results of the QCA for negative outcomes of component B of PM KUSUM . . . 43
  - 5.3.3 General observations from the results . . . 45
- 5.4 Additional insights gained from thematic analysis . . . 45
- 5.5 Sensitivity and robustness analysis . . . 47
  - 5.5.1 Lowering or increasing consistency threshold . . . 47

5.5.2 Changing calibration thresholds 49

6 Discussion and Conclusion 52
6.1 Discussion 52
6.1.1 Discussion on the results of QCA and thematic analysis 52
6.1.2 Broader discussions 53
6.2 Comparison to existing literature and academic contributions 54
6.3 Conclusions 55
6.4 Limitations of Study 58
6.5 Policy recommendations 58
6.6 Future scope of research 59

References 60

A Appendix A 66
A.1 Description of components A and C 66
A.2 Search terms used for identification of factors which influence solar adoption in agriculture 68
A.3 Literature on factors identified 69

B Appendix B 71
B.1 Distribution plots of Raw Data 71
B.2 Raw Data for component B variables 76
B.3 Calibrated data for component B variables 77
B.4 Truth Table for Component B positive and negative outcomes 78
B.5 Replacing the variable representing irrigation demand with the number of diesel pump-sets 79

C Appendix C 82
C.1 Questionnaire for semi structured interview with think tank experts and academia 82
C.2 Expert Pool 83
C.3 Implementation in Maharashtra 84

List of Figures

1.1 Estimated stock of pump-sets by the source of powering from the years 2010-2022(IEA, 2020) . . . 1
1.2 Indian agricultural CO_2 emissions in million tonnes, 2011-2022 estimates(CEIC, 2022) . 2
1.3 Average cost of diesel over the years 2004-2024(SkillsHats, 2024) . . . 2
1.4 India GHI average in 2011 kWh/m^2(SolarGIS, 2011) . . . 3
1.5 Component B installed quantities per sanctioned quantities as a percentage(MNRE, 2019) 4

2.1 Cumulative number of solar irrigation pumps installed in India with decline in prices of solar PV(Durga and Gaurav, 2024 and Ritchite et al., 2024) . . . 9
2.2 Components of the PM KUSUM scheme and their objectives(Rahman et al., 2021) . . . 10
2.3 Component B subsidy structure and key features . . . 11

4.1 Mixed Methods Visual representation for Sequential - Explanatory Designs(Ivankova et al., 2006) . . . 19
4.2 Recommended steps for fsQCA(Pappas and Woodside, 2021) . . . 22
4.3 Component B sanctioned pumps per net area sown calibration . . . 28
4.4 GSDP per capita calibration . . . 29
4.5 Farmers monthly incomes calibration . . . 30
4.6 Annual irrigation draft per net area sown calibration . . . 30
4.7 Solar RPO percentages calibration . . . 31
4.8 Ideological alignment of national and regional government calibration . . . 31

5.1 Results of fsQCA for positive outcomes component B . . . 39
5.2 Results of fsQCA for negative outcomes of component B . . . 43
5.3 Results of fsQCA for positive outcomes component B with a consistency threshold set at 0.85 . . . 47
5.4 Results of fsQCA for positive outcomes component B with a consistency threshold set at 0.75 . . . 48
5.5 Observed solution pathways for positive performance with a 5% increase in calibration thresholds . . . 49
5.6 Observed solution pathways for negative performance with a 5% increase in calibration thresholds . . . 50
5.7 Observed solution pathways for positive performance with a 5% decrease in calibration thresholds . . . 50
5.8 Observed solution pathways for negative performance with a 5% decrease in calibration thresholds . . . 51

B.1 Component B outcome distribution . . . 71
B.2 Farmer monthly income distribution . . . 72
B.3 GSDP per capita distribution plot . . . 72
B.4 RPO distribution plot . . . 73
B.5 Annual irrigation draft per net area sown distribution plot . . . 73
B.6 Ideological alignment of national and regional government . . . 74
B.7 No of Diesel Pump-sets distribution plot . . . 74
B.8 No of Diesel Pump-sets calibrated plot . . . 75
B.9 Solution outcomes of the positive outcomes where the irrigation demand is replaced with number of diesel pump-sets . . . 79
B.10 Solution outcomes of the negative outcomes where the irrigation demand is replaced with number of diesel pump-sets . . . 80

C.1 Maharashtra Pumps Installed(MNRE, 2019) 84
C.2 Maharashtra reasons for successful implementation of PM KUSUM component B(Authors Analysis) 86

List of Tables

3.1 Summary of findings from literature of factors identified closely co-relating to adoption of solar in agricultural context 15

4.1 Calibration thresholds recommended by Pappas and Woodside, 2021 23
4.2 Factors Type, Factor and their consideration or non consideration for QCA 25
4.3 Factors, data selected, data source, Year and Frequency of Data collection (All data is collected state wise) 27
4.4 Causal Conditions and Corresponding Dataset Notations, Distribution Types, and Thresholds(in percentiles and numbers) 29

5.1 Raw Dataset for Installed pump-sets as a percentage of the sanctioned pump-sets(MNRE, 2019) 36
5.2 Fuzzy-set values and their membership(Singh, 2022) 36
5.3 The codes identified from thematic analysis and the number of respondents who mentioned the topic around the code(Authors Analysis) 38

A.1 Summary of findings from literature of factors identified closely co-relatinng to adoption of solar in agricultural context 70

B.1 Raw data of the Installed/Sanctioned percentage and the variables to be tested 76
B.2 Calibrated Dataset 77
B.3 Truth table component B positive outcomes 78
B.4 Truth table component B negative outcomes 78

C.1 Experts their level of involvement, type of institution they are involved with, and weather they are actively consulting the government on the policy right now 83

Nomenclature

Abbreviation	Definition
GHG	Greenhouse Gases
MoA&FW	Ministry of Agriculture and Farmers Welfare
IEA	International Energy Agency
DISCOM	Distribution Company
PV	Photovoltaic
RPO	Renewable Purchase Obligations
MNRE	Ministry of New and Renewable Energy
PM KUSUM	Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan
IPS	Individual Pump Solarization
FLS	Feeder Level Solarization
PIB	Press Information Bureau
FEEM	Fondazione ENI Enrico Mattei
CAP	Common Agricultural Policy
SFA	Stochastic Frontier Analysis
PPAP	Photovoltaic Poverty Alleviation Projects
CBA	Cost Benefit Analysis
LEAP	Low Emissions Analysis Platform
WEF	Water Energy Food
UN	United Nations
MNES	Ministry of Non-conventional Energy Sources
DC	Direct Current
JNNSM	Jawaharlal Nehru National Solar Mission
SIP	Solar Irrigation Pumps
CGIAR	Consultative Group for International Agricultural Research
SKY	Suryashakti Kisan Yojana
SSY	Saur Sujala Yojana
MSKVY	Mukhyamantri Saur Krushi Vahini Yojana
JOHAR	Jharkhand Opportunities for Harnessing Rural Growth
FiT	Feed In Tariff
HP	Horsepower
NISE	National Institute of Solar Energy
NABARD	National Bank for Agriculture and Rural Development
PFC	Power Finance Corporation
REC	Rural Electrification Corporation
QCA	Qualitative Comparative Analysis
MOSPI	Ministry of Statistics and Programme Implementation
CFA	Central Financial Assistance
NSS	National Sample Survey
bcm.	Billion Cubic Meters
GOI	Government of India
csQCA	Crisp set qualitative comparative analysis
mvQCA	Multi value qualitative comparative analysis

Abbreviation	Definition
fsQCA	Fuzzy set qualitative comparative analysis
GSDP	Gross State Domestic Product (per capita)
NSSO	National Sample Survey Office, India
INSB	Installed/Sanctioned pumps (%)
FMI	Farmers Monthly Incomes in Rs.
ALI	Ideological alignment of state government with national governments
AID	Annual groundwater irrigation draft per net area sown
TA	Thematic Analysis
FY	Financial Year

1

Introduction

1.1. Background

The global greenhouse gas emissions contributed by agricultural sector is rising year after year, with the increasing food production. Energy use in agriculture is crucial for maintaining productivity, and reducing the impact of energy shortages on farm productivity(Stout, 1984). This energy, predominantly sourced from fossil fuels, directly or indirectly contributes to greenhouse gas (GHG) emissions from agriculture. Solarization[1] in agricultural practices could prove as one of the potential solutions, of many, for the reduction in greenhouse gas emissions while delivering the energy use for the agricultural practices. The adoption of solar in agriculture could satisfy many requirements including the need for irrigation, production of electricity for the farmland and greenhouse operations(Chel and Kaushik, 2011).

In India, the rapidly growing population places increasing pressure on the agricultural sector to meet rising food demands. It was noted that about 45% of net land in India is used for agricultural purposes especially exacerbating the freshwater need, essential for crop production(MoA&FW, 2023). Close to 80% of the limited freshwater resource in India is used for agricultural purposes(Pandey et al., 2020). In 2019, an economic survey by the ministry of finance noted that almost 89% of water extracted is through groundwater for irrigation with the means of pumps, either electrically powered or diesel powered(Beaton et al., 2019). International Energy Agency in 2020 estimated that the total estimated stock of irrigation pump-sets in India to facilitate the groundwater irrigation would be 31.8 million pump-sets(IEA, 2020). Of this the electric pump-sets are estimated to contribute around 64%, while diesel pump-sets are estimated to contribute 28% while solar pump-sets would only contribute to 8% of total irrigation pump-sets(see Figure 1.1)

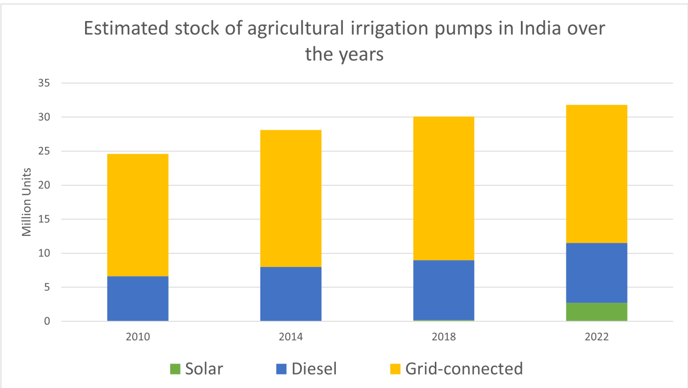

Figure 1.1: Estimated stock of pump-sets by the source of powering from the years 2010-2022(IEA, 2020)

[1]Solarization refers to the usage of solar energy based technologies(photovoltaics, concentrated solar or other technologies associated with generation of energy using solar power)

Of the total pump sets in India powering groundwater irrigation in 2022, it is estimated that close to 2.2 million pump sets were powered by diesel generators(IEA, 2020).Studies indicate that these diesel pump sets use close to 5.52 billion liters of diesel annually emitting equivalent of 15.4 million tonnes of CO_2 annually(Chateau et al., 2023). This diesel usage heavily contributes to the estimated Indian CO_2 emissions from the agricultural sector which amounts to close to 32 million tonnes of CO_2 equivalent and is increasing year on year(CEIC, 2022, See Figure 1.2).

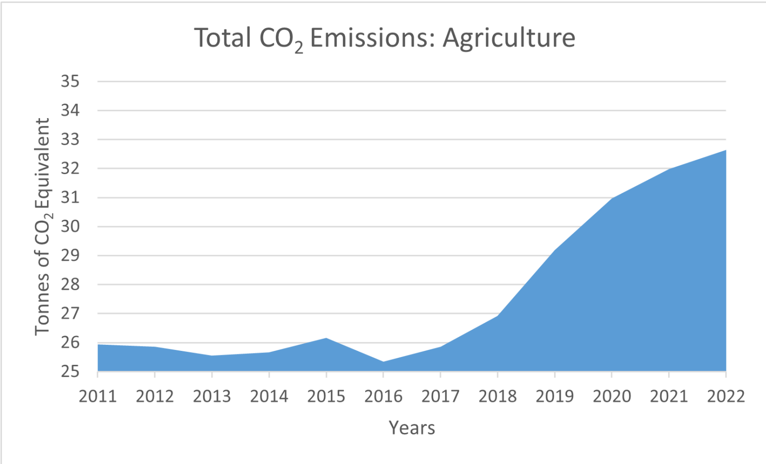

Figure 1.2: Indian agricultural CO_2 emissions in million tonnes, 2011-2022 estimates(CEIC, 2022)

India's domestic crude oil production accounts for only 13% of its total oil supply, with the remaining 87% sourced through imports (IEA, 2024). This significant reliance on imported oil not only places a burden on the economy but also raises concerns about energy security. The substantial rise in diesel prices over the years has significantly increased input costs for farmers relying on diesel pump sets(Khanna, 2024). Figure 1.3 highlights this trend, illustrating the escalating diesel prices over the span of the last 20 years.This financial strain, coupled with unreliable electricity access, has prompted both farmers and policymakers to explore alternative solutions to reduce dependency on diesel for irrigation

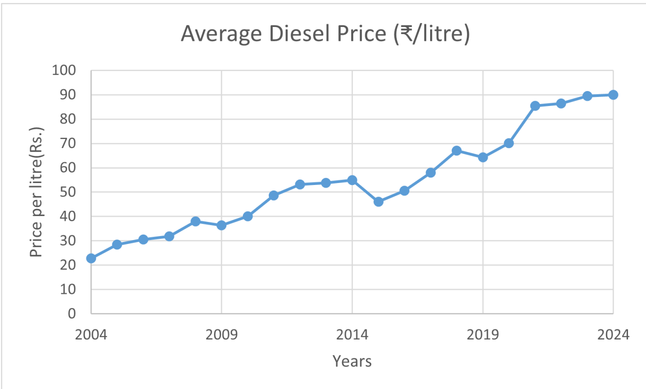

Figure 1.3: Average cost of diesel over the years 2004-2024(SkillsHats, 2024)

India, being geographically blessed has an opportunity to utilize its solar resource to produce electricity with the help of photovoltaic panels which in turn could satisfy farmers irrigation needs(see Figure 1.4). Solarization of agriculture using photovoltaic[pv] panels and solar pumps was suggested as a possible alternative to alleviate the financial burden on the state while giving incentives to DISCOMs to achieve renewable purchase obligations[RPO], simultaneously providing the farmers direct access to electricity for irrigation and reduce overall CO_2 emissions(Adhikari, 2020). Large scale solarization of agriculture would also reduce GHG emissions by denting on the usage of diesel pump-set and reducing the reliance on electricity sector to power the irrigation pumps, of which close to 61% still being produced by conventional energy resources like coal, lignite, natural gas and diesel(Hore et al., 2023). All of these factors and the inter-related nature of the energy and agricultural domains required a policy which addresses the challenges mentioned.

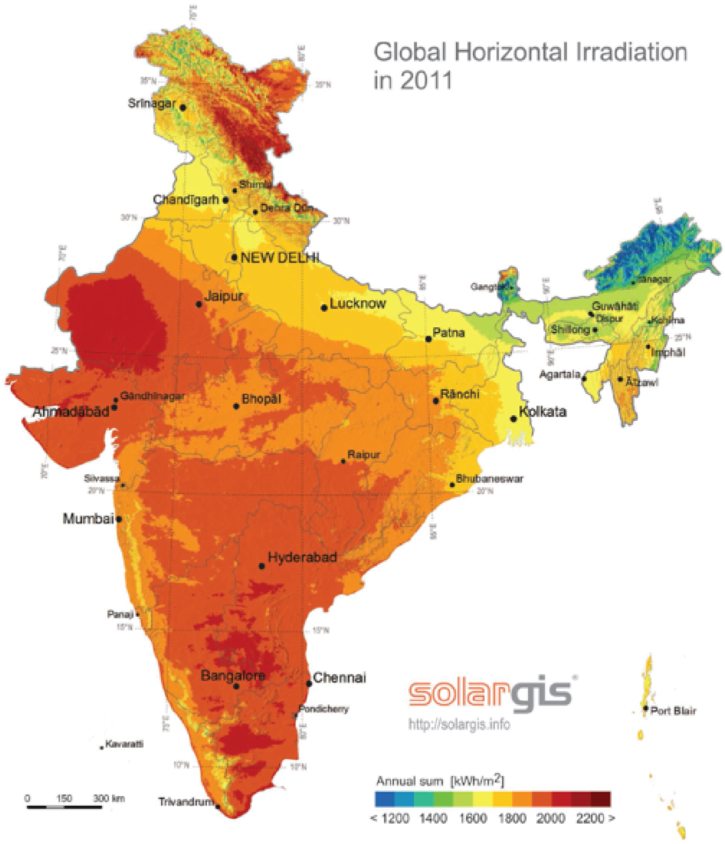

Figure 1.4: India GHI average in 2011 kWh/m^2(SolarGIS, 2011)

PM-KUSUM

In 2019, to address some of these concerns and utilize the abundant solar resource the Government of India proposed the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan[PM-KUSUM] scheme to encourage use of photovoltaics to generate electricity and power the water pumps for irrigation(MNRE, 2019).The PM-KUSUM scheme seeks adoption of both grid connected and off grid photovoltaic installations primarily being used for irrigation purposes. The scheme is structured in three components: Component A is directed towards setting up of decentralized solar power plants on agricultural lands; Component B aims towards replacing diesel pumps with up stand alone solar pumps for irrigation; Component C focuses on solarizing existing grid connected pumps either through individual pump solarization[IPS] or feeder level solarization[FLS]. Through this scheme the government of India seeks to decrease dependence on diesel and electric generators for irrigation and equipping the farmers with possible additional revenues with the added benefit of reduction of GHG emissions. The scheme also gives an opportunity to DISCOMs of different states to relieve the stress on their network and finances by phasing out the subsides provided by them to the farmers(Mukherji, 2020).

The central[2] Indian administration which is responsible for the implementation of the scheme has set aside a fund to aide the execution of the scheme by the different states[2], which can avail parts of the fund while covering some parts of the scheme under the state budget according to the demand and the components of the scheme that the states choose to promote(MNRE, 2019). More incentives are

[2] The Indian government is structured federally with the central government and the state governments both responsible for different aspects of governance but generally the central government will control the flow of finances generated through tax revenues especially for centrally promoted schemes.

present to the states which perform well in the installation based on reaching certain milestones. The dynamics of the interaction between the central and the state levels of the Indian administration are essential components of the on ground implementation of the scheme.

The latest MNRE data revealed that Component A and C have significantly under performed with only 3% and 0.4% of sanctioned capacities being installed(PIB, 2023). Component B of the scheme has seen much higher installations but of the 26 states and union territories that have adopted this component of the scheme we can see some significant disparities in the installations(See figure 1.5). This variation of the component B performance, hints at a potential disparity in policy effectiveness and performance. Factors such as sub-national autonomy, could have facilitated policy innovation which have driven higher adoption rates in states which tend to be early innovators. Intergovernmental relations from the central to state level, as emphasized by Montpetit, 2002, are also crucial for policy success. Additionally, Atteridge et al., 2012 stress on the importance of local government in addressing farmers' concerns, while Reimer and Prokopy, 2014 underscore the role of state resource prioritization in shaping policy outcomes. Despite some insights, academic literature lacks a focused discussion on solar adoption in agriculture, often overlooking regional contexts and favoring singular explanations for policy performance. This has led to an incomplete understanding of how local conditions impact the success or failure of solar initiatives, such as the PM-KUSUM scheme, across different states. They do not dive deeper into the how the differences in the farmer and farming attributes/practices, economic, political, stakeholders, policy design and mechanisms, and how a combinations of factors from these domains have an effect on the potential variations that are observed in the performance of the scheme. Clarifying these gaps could significantly enhance our understanding of the current differences in policy outcomes observed between the states.

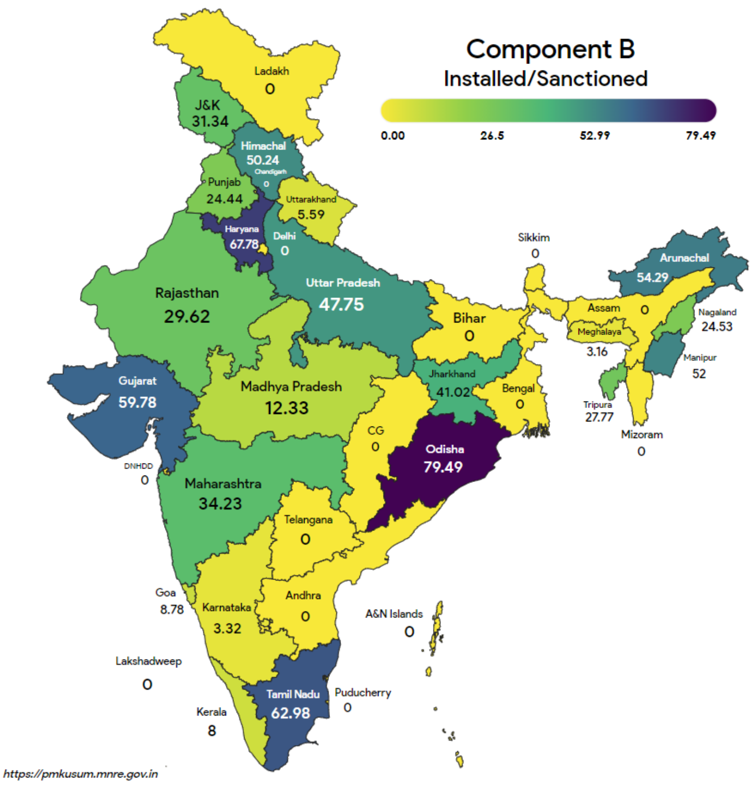

Figure 1.5: Component B installed quantities per sanctioned quantities as a percentage(MNRE, 2019)

1.2. Research gap and objective

The significant variation in policy outcomes for the solarization of irrigation and, more broadly, agriculture across Indian states warranted an in-depth exploration. While literature existed which addresses policies related to solarization in these areas, there is a lack of detailed evaluations specifically investigating the state-level differences in these outcomes. Although solarization policies for irrigation and agriculture in India have not been extensively explored in academic literature, evaluations in the broader fields of energy and agriculture can help pinpoint key research gaps. These two domains are closely intertwined within the scope of the policies being studied, making their interplay crucial to understanding policy outcomes.

Authors such as Madau et al., 2014 and Wang et al., 2020 offer valuable insights into policy evaluations in related fields by focusing primarily on the impacts of policies rather than commenting on their performance. For instance, Madau et al., 2014 employed the Fondazione ENI Enrico Mattei (FEEM) assessment tool to analyze the Common Agricultural Policy (CAP) in Europe, identifying contradictions and causal links while evaluating policy impacts. Similarly, Wang et al., 2020 utilized stochastic frontier analysis (SFA) to assess the efficiency of photovoltaic poverty alleviation projects (PPAP), emphasizing socio-economic factors like age, education, and income as key determinants of project impact. Both studies, while valuable in analyzing policy impacts, lack considerations of regional differences and contextual factors, an issue particularly relevant when dealing with diverse socio-economic and institutional environments.

When examining solarization policies for irrigation and agriculture, ex-ante evaluations dominate the existing literature, providing projections of potential impacts but often failing to address regional variations. For example, Bassi, 2018 and Moradi et al., 2023 conducted ex-ante evaluations using cost-benefit analysis (CBA), with Moradi et al., 2023 preferring the LEAP tool to assess the electrification of agricultural wells in Iran. Moradi et al., 2023 acknowledged limitations in addressing provincial differences and potential biases in scenario selection. Similarly, Bassi, 2018 assessed the viability of solar irrigation in India, but their generalization across eastern and western regions overlooks nuanced differences between states. Notably, both these studies focus on evaluating projected impacts of solarization policies, similar to Madau et al., 2014 and Wang et al., 2020, but diverge in their methodologies, emphasizing the limitations of tools like CBA.

Likewise, Adhikari, 2020, in their ex-ante analysis of policies for solar-powered irrigation in India, identified drivers and barriers to solar adoption for irrigation. These drivers and barriers were categorized into economic, social, environmental, and institutional themes, aligning closely with the socio-economic factors highlighted by Wang et al., 2020. However, like Bassi, 2018 and Moradi et al., 2023, Adhikari, 2020 generalized its findings across India, failing to address the critical regional variations that influence policy success or failure. This overlap in the generalized approach across these studies underscores a broader gap in the literature concerning the role of regional and contextual factors in shaping policy outcomes.

In light of these studies, there is a clear lack of research exploring the contextual factors driving divergent policy outcomes for the solarization of irrigation and agriculture across Indian states. It is essential to capture the complex interplay of socio-economic, environmental, and institutional factors that shape policy effectiveness while accounting for regional variations that influence policy uptake. Moreover, key evaluations of solarization policies for irrigation and agriculture in India—such as those by Bassi, 2018 and Adhikari, 2020—are primarily ex-ante studies projecting potential impacts or identifying barriers and drivers. There is a pressing need for evaluations that analyze real-world policy performance through in-media res or ex-post assessments.

This review of the literature identifies the following research gaps:

- A predominant focus on ex-ante evaluations, with limited in-media res or ex-post studies.
- A lack of studies assessing policy performance after implementation, as the existing literature largely focuses on projected policy impacts.

- Limited discussion on the combination of factors that directly or indirectly influence policy outcomes for the solarization of irrigation and agriculture.
- A lack of studies addressing the causal complexity of these factors and their combined effects, particularly in the context of regional variations.

1.3. Main research question and sub questions

Through the above discussion it has been made clear that there is a lack of an evaluation of the policy for solarization of irrigation in India which leads us to the following main research question:

Why are there disparities in the performance of the policy aimed at replacing diesel pumps with solar irrigation systems across states in India?

Research sub questions

To answer the main research question and to evaluate the policy the steps of the research are broken down into further sub research questions:

1. What factors could possibly affect the adoption of solar energy in agricultural irrigation practices, particularly in the context of policies addressing this adoption?
2. How do combinations of these factors contribute to variations in policy outcomes for the solarization of irrigation across different states in India?
3. What explains the different combinations of factors influencing regional adoption of solar water pumps under the policy?

1.4. Relevance of Thesis

Policy plays a critical role in the early adoption of renewable energy technologies, and the PM KUSUM initiative exemplifies this by addressing the solarization of a sector vital to national needs. Numerous factors can influence the policy's outcomes, contributing to observable differences at the state level. Understanding these factors is essential for identifying areas for improvement during the early phases of implementation and for refining existing policies. With PM KUSUM set to remain in effect until March 2026 and having generated outcomes since its inception in 2019, this is an opportune moment to evaluate the policy and its impact on solar adoption in agriculture. While there have been studies on solarization efforts in India and globally, a detailed evaluation of this specific policy post-implementation has yet to be conducted.

This thesis significantly contributes to the field of Sustainable Energy Technology by investigating the role of policy in promoting renewable energy adoption within agriculture. By focusing on the PM KUSUM policy, the research examines the factors that lead to disparities in solarization outcomes across various states. This exploration highlights the trans-formative potential of solar energy in agricultural practices while addressing the socio-political and implementation challenges that can impede progress. The insights gained from this study are essential for informing future policies and strategies aimed at optimizing renewable energy solutions, ultimately supporting the global transition toward sustainable energy systems.

1.5. Outline of thesis

This thesis aims to deepen the understanding of policy outcomes related to solarization in Indian agriculture, specifically in irrigation. The focus is on investigating factors that influence solar installations made through the policy at the state level. Impacts on the Water-Energy-Food (WEF) nexus, aside from those directly related to solar installations under the scheme, will not be studied, as these would be challenging to discern at the state level and would broaden the scope beyond feasibility within the stipulated timeline. Component B of the PM KUSUM scheme is the focus of this study, as it has shown significant implementation outcomes, unlike Components A and C, which have not yet achieved substantial traction.

Through a comprehensive review of academic and non-academic literature, this thesis identifies potential factors affecting solar capacity installed under the policy. To achieve the objective of examining state-level factors influencing solar adoption through the policy, a mixed-methods approach is adopted, using data obtained from governmental and non-governmental statistical reporting agencies, supplemented by insights from semi-structured interviews. The findings aim to illuminate the extent to which identified factors impact solar adoption in agriculture across states, while also exploring interdependencies within these factors that may reinforce adoption rates in certain states under the scheme. The qualitative analysis further investigates possible explanations for the combinations of identified factors, as well as the influence of policy design and the roles of other stakeholders on the observed differences in outcomes.

The thesis unfolds as follows: Chapter 2 provides a background on the PM KUSUM policy, detailing its components and notable features. Chapter 3 elaborates on factors identified in the literature that could potentially explain the observed differences in policy outcomes across states. Chapter 4 outlines the research approach and methodologies used, laying the foundation for both qualitative and quantitative methods. Chapter 5 presents the results of the QCA analysis and thematic analysis. In the final chapter, based on the findings from the previous chapters a comprehensive understanding of state-level differences in solar adoption under the policy is gained. This chapter specifically dives into a discussion on policy performance and state-level differences, followed by a comparison to existing literature, a discussion on the conclusions of the thesis by addressing each research sub question and the central research question, an outline of the study's limitations, and recommendations for policy improvement as well as suggestions for future research directions.

2

About the Policy: PM KUSUM

This chapter provides a detailed discussion of the policy for solarization of agriculture in India, offering essential context and a nuanced understanding of the policy framework. This understanding is critical for exploring the factors that contribute to variations in policy performance across states. Section 2.1 details introduction to the origins of agricultural solarization policies in India, presenting a brief background to set the stage. Section 2.2 then delves into the PM-KUSUM scheme, with a particular focus on Component B, which targets the installation of solar-powered pumps. Finally, the section 2.3 concludes with a discussion of the policy's key features that were most relevant to this research.

2.1. Background

Agriculture is a prime occupation in the nation with almost 54.6% of population involved in agriculture(MoA&FW, 2023). Also with a growing population, with an annual growth rate of close to 1% over the last decade, there is an emphasis on the increasing of food production(UN, 2024). This makes agriculture a highly energy-intensive sector, consuming around 18% of the country's electricity and approximately 5.52 billion liters of diesel annually(Chateau et al., 2023; Durga and Gaurav, 2024). With the majority of India's crude oil being imported and only 13% of demand met by domestic production, the reliance on diesel for agricultural activities places a significant strain on the national economy(Martin et al., 2023). In addition to diesel consumption, much of the electricity for agriculture is provided at highly subsidized rates, or even free in some cases, as part of farm power subsidies. The financial burden of these subsidies falls on state governments or government-owned distribution companies, costing the exchequer close to Rs. 120 billion in 2024 alone(Durga and Gaurav, 2024). Irrigation remains the major contributor to energy use in farming, underscoring the need for a more sustainable approach.

In the recent decades the integration of solar photovoltaics in agricultural contexts has emerged as an alternative to provide electricity required for irrigation. This energy is provided through individual solar farms or through grid-connected or off-grid solar pumps to irrigate the farms. The uptake of solar integration is also true for the Indian context, with interest in solar integration in agriculture dating back to the early 2000s with Radulovic, 2005 citing the scheme by the government of Punjab under the direction of then Ministry of Non-conventional Energy Sources[MNES],(now MNRE) to promote installation of solar water pumps. This pilot though did not lead to large scale integration immediately.

It was in 2010's that solar photovoltaics integration for agriculture started taking shape. Many schemes and pilots on the state level were experimented with different models of implementation spurring the growth of use of photovoltaics in Indian agricultural contexts. In 2009, the state department of horticulture in Rajasthan, often referred to as pioneers experimented with setting up of DC solar irrigation pumps(Goyal, 2013). In 2012 another notable pilot program was set up in the state of Bihar (Durga and Gaurav, 2024). In 2010, the Jawaharlal Nehru National Solar mission[JNNSM] was introduced(IEA, 2014). This also propagated the integration of solar in activities. However, it was only a small component until 2014, when the government of India announced the expansion of JNNSM with the target to install 100,000 SIP by 2020-21(PIB, 2014).

The experimentation around pilots for solar integration in agriculture took up around mid 2010's with further pilot programs popping up across India. In Gujarat, a grid connected solar co-operative was tried by a few farmers around 2014-15("CGIAR", 2020). A similar experiment was tried in another village in Gujarat around 2018-19. Around 2014-15, in Karnataka, Surya Raitha scheme was implemented(Durga et al., 2021). Surya Raitha, was the first feeder level pilot of grid connected solar pumps. In 2017-18,government of Gujarat after monitoring the success of the first pilot implemented Suryashakti Kisan Yojana [SKY] with the objective of further solarization of irrigation pumps for close to 4200 farmers(Pasupalati et al., 2022). Another grid connected pilot was implemented in Andhra Pradesh which replaced existing electric pumps with SIP powered by brush-less DC motors. Off grid connected SIP also rose to prominence where the grid connections are not a feasible option. Around 2018, off-grid solar irrigation pump was adopted in the states of Chattisgarh and Jharkhand. In Chattisgarh, Saur Sujala Yojana (SSY) was launched in 2018. By 2022, the state had the maximum number of SIPs(Khanna, 2024). In Jharkhand, Jharkhand Opportunities for Harnessing Rural Growth[JOHAR], was launched to diversify farm incomes in 17 districts in Jharkhand(Durga and Gaurav, 2024).In 2017, the government of Maharashtra set up Mukhyamantri Saur Krushi Vahini Yojana[MSKVY] promoting setting up of distributed power plants in the state(Nathan et al., 2023). All these pilots worked with varying types of deployment strategies. Over the years the increase in installed capacity of solar water pumps has coincided with the global cost decrease(See figures 2.1). As the cost of solar photovoltaics and solar powered irrigation pumps start to drop, and with the abundant solar resource available in India to be utilized, around 2019, the government of India announced the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan[PM KUSUM]. This scheme took inspiration from the pilots which preceded it to focus on solarization of Indian agriculture by providing options for centralized, distributed and feeder level solarization[FLS].

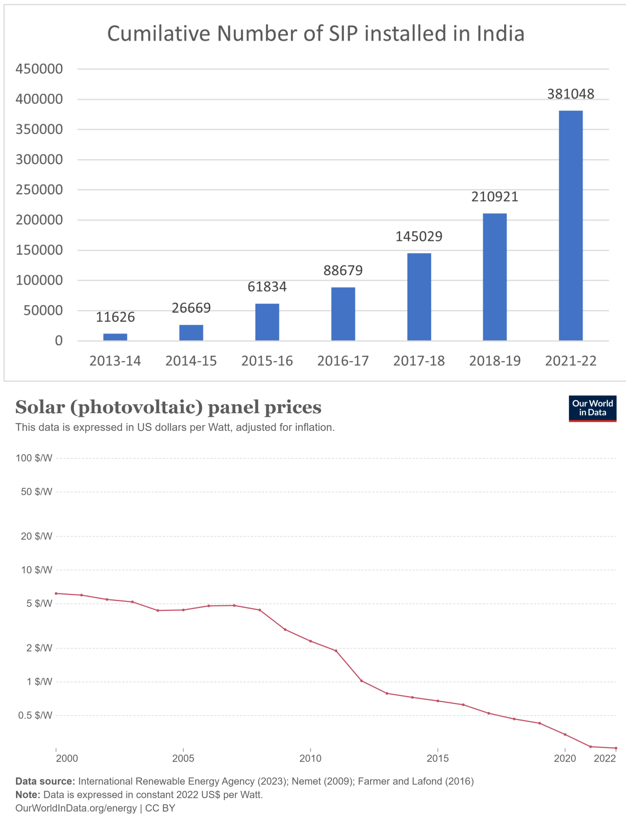

Figure 2.1: Cumulative number of solar irrigation pumps installed in India with decline in prices of solar PV(Durga and Gaurav, 2024 and Ritchite et al., 2024)

2.2. PM KUSUM

Introduced in 2019, Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan[PM KUSUM], aims to add solar capacity of about 34,800 MW by 2026 with the total central financial support of Rs. 34,422 crore (MNRE, 2019). The objective of the scheme are as follows: provide a boost to farmers incomes while improving irrigation access, reduction of the agricultural sector's "dependency on fossil fuels", and to alleviate the recurring subsidies of agriculture energy supply(Rahman et al., 2021).

The Indian administration, responsible for executing the scheme, has earmarked a dedicated fund to support its implementation across various states. While states can tap into this fund, they also bear some responsibility for financing certain aspects of the scheme through their own budgets, based on demand and the specific components they prioritize (PIB, 2023). Furthermore, states that excel in achieving installation milestones receive additional incentives. Under the scheme, farmers receive substantial financial support for solar installation.

Components of PM KUSUM

The scheme is divided into three components: Component A focusing on installation of decentralized solar plants; Component B directing setting up of stand alone solar pumps to replace diesel pumps; Component C focusing on the solarization of grid-connected pumps by replacing them through feeder level solarization[FLS] or individual pump solarization[IPS](Figure 2.2). The description of the policy in this particular study is restricted to the component B of the policy only as the study focuses on the regional differences in installations of component B of PM KUSUM. The descriptions of components A and C are provided in appendix A.1.

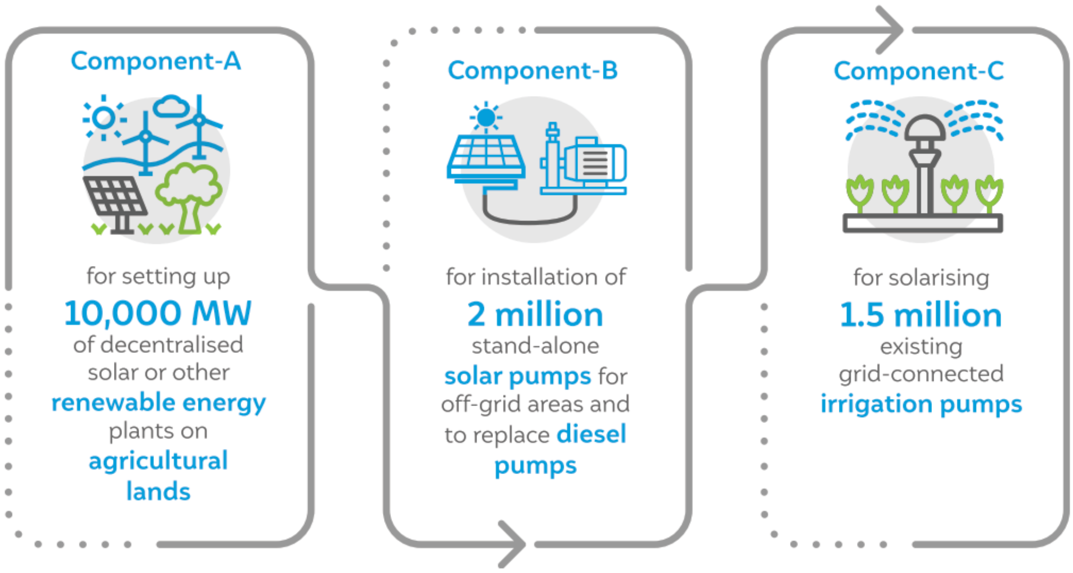

Figure 2.2: Components of the PM KUSUM scheme and their objectives(Rahman et al., 2021)

Component B

This component of the scheme is primarily focused on the de-dieselization of off-grid pumps(MNRE, 2019). "Individual farmers will be supported to install standalone solar agriculture pumps of capacity up to 7.5 HP in off-grid areas, where grid supply is not available"(MNRE, 2019).Under component B, the provision of CFA will be limited to solar pumps of up to 7.5 HP to discourage over sizing of solar pumps. 30% of the capital cost is provided as central financial assistance, with an additional 30% contribution from the state government. Farmers are responsible for covering the remaining 40% of the capital cost as shown in figure 2.3. However, they have the option to avail themselves of a loan financing option to cover 30% of the 40%. This leaves only 10% of the capital cost to be directly paid by the farmer at the time of installation(MNRE, 2019). In some states/union territories the subsidy provided by the central government is increased to 50% of capital costs while state government covers 30%

leaving only 20% to be covered by the farmers. This components took inspiration from the pilots and experiments carried out in Chattisgarh and Jharkhand, providing with access to electricity where there is no proper grid infrastructure(Pasupalati et al., 2022). The stand alone nature of the solar pumps makes it easier to install and mobile.

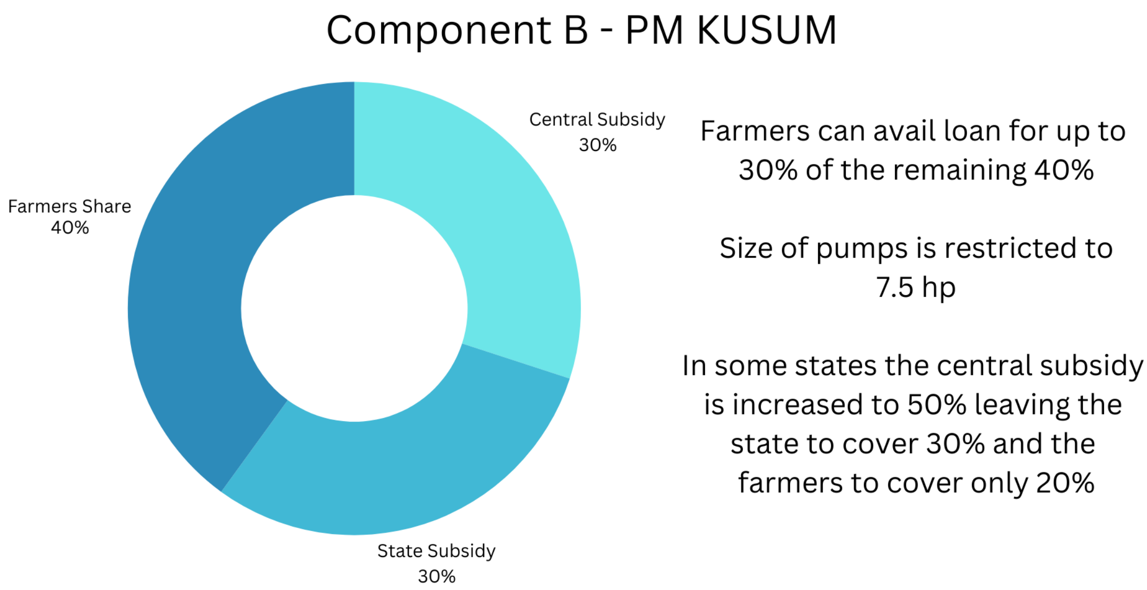

Figure 2.3: Component B subsidy structure and key features

2.3. Salient features of PM KUSUM

To add to the above description of the policy and component B there are some features of the policy which could prove to be critical to broaden the context. A Screening Committee under the MNRE Secretary approves state-wise allocation of targets set for every component of PM KUSUM (sanctioned quantities) on the basis of overall target of the year and demand received from implementation agencies, highlighting the demand based nature of the scheme(Adhikari, 2020; MNRE, 2019). The sanctioned quantities also could be adjusted based on demand from different states. This process of readjustment was last carried out in July 2024 as well to match up with the rate of installations in different regions in India. The scheme discourages the setting up of solar water pumps in dark/grey zones of water availability unless it is proven to replace grid connected or diesel pumps(Adhikari, 2020). The scheme also encourages setting up of micro and drip irrigation set-ups for especially water distressed areas while combining with solar for electricity provided.

The state governments have complete autonomy on the choosing of the implementing agency for different components of the PM KUSUM scheme with the states not requiring a singular implementing agency to take charge of the scheme's implementation across components(MNRE, 2019). There are some technical guidelines which are to be followed for the installation of solar pumps which are designed with the help of National Institute of Solar Energy [NISE] and all implementing agencies have to abide by the same(MNRE, 2019). The state implementation processes although could be tailored according to the requirements in the state and the resources of the state implementing agency(MNRE, 2019). The implementing agencies have the onus of procuring the pumps for the implementation at the state level and they can only procure pumps from an approved list of vendors provided by the Ministry of New and Renewable Energy. Often the state implementing agencies tender the quantities that they intend to install in a given period giving the interested and approved vendors an opportunity to participate in the bidding process to supply with the required capacity.

PM KUSUM embodies a forward-thinking approach aimed at fostering sustainability and ensuring equitable access to solar pump systems within the socio-economic landscape of agriculture. With a primary emphasis on affordability, the scheme targets small and marginal farmers, offering solar pumping systems at a subsidized rate under all the components, while also enabling them to sell surplus solar power back to the grid if connection is enabled.

3

Factors which can influence solar adoption in agriculture

Building up on the insights gained about the policy and to further explore the reasons for the adoption or non adoption of solar energy for irrigation this chapter identifies the key factors commonly associated with the adoption of solar technology in agriculture, particularly for irrigation. Most existing studies on factors influencing the adoption of solar for irrigation focus predominantly on farmer-level insights. To broaden the perspective, this research also considers regional factors influencing solar adoption in agriculture. By integrating both farmer and regional contexts, the analysis aims to uncover themes and potential drivers for the adoption of solar irrigation systems.

Table 3.1 highlights key authors and their findings regarding the factors that significantly influence solar energy adoption in agriculture. Authors highlighted in blue have specifically identified factors affecting the adoption of solar irrigation specifically, while the other studies had a slightly borader focus of adoption of solar in agiculture. The search terms used to identify these factors in the literature are detailed in Appendix A.2. While many studies rely on surveys of individual farmers, some also explore regional drivers (Ge et al., 2017; Schaffer and Düvelmeyer, 2016). This comprehensive review helps identify factors that could play a crucial role in promoting solar energy adoption in agricultural practices.

Type	Factor	Authors
Economic (Macro)	Regional per capita income	Borchers et al., 2014
Economic (Micro)	Farmer incomes	Powell et al., 2021; Rathore et al., 2018; Sunny et al., 2022, Agir et al., 2023; Beckman and Xiarchos, 2013; Kata et al., 2021; Sutherland et al., 2016; Tate et al., 2012
Economic (Micro)	Existing farmer debt	Powell et al., 2021; Rathore et al., 2018, Tate et al., 2012
Economic (Micro)	Payback Period for technology installed	V. Kumar et al., 2020, Agir et al., 2023; Tate et al., 2012

Economic (Micro)	Capital cost of technology installed	Adhikari, 2020; Agrawal and Jain, 2019; V. Kumar et al., 2020, Agir et al., 2023; Beckman and Xiarchos, 2013; Tate et al., 2012
Social	Age of the farmer	Beckman and Xiarchos, 2013; Ge et al., 2017; Kata et al., 2021; Li et al., 2021; Schaffer and Düvelmeyer, 2016; Sutherland et al., 2016; Tate et al., 2012
Social	Education level of the farmer	Rana et al., 2021; Sunny et al., 2022, Beckman and Xiarchos, 2013; Li et al., 2021; Moerkerken et al., 2023; Ruiz-Fuensanta et al., 2019; Schaffer and Düvelmeyer, 2016; Sutherland et al., 2016; Tate et al., 2012; Wagner et al., 2024
Social	Internet access	Beckman and Xiarchos, 2013; Borchers et al., 2014
Social	Awareness	Agrawal and Jain, 2019; V. Kumar et al., 2020; Rathore et al., 2018; Sunny et al., 2022, Agir et al., 2023; Li et al., 2021; Moerkerken et al., 2023; Wagner et al., 2024
Energy	Energy/electricity costs	Beckman and Xiarchos, 2013; Kata et al., 2021
Energy	Energy demand of the farm	Ge et al., 2017; Kata et al., 2021
Energy	Solar irradiance	Agrawal and Jain, 2019, Borchers et al., 2014; Ge et al., 2017
Agriculture	Farm size	Rana et al., 2021, Borchers et al., 2014; Ge et al., 2017; Kata et al., 2021; Li et al., 2021; Ruiz-Fuensanta et al., 2019; Schaffer and Düvelmeyer, 2016; Sutherland et al., 2016; Tate et al., 2012

Agriculture	Farm type/Crop type	Agrawal and Jain, 2019, Beckman and Xiarchos, 2013; Ge et al., 2017; Kata et al., 2021; Li et al., 2021; Ruiz-Fuensanta et al., 2019; Schaffer and Düvelmeyer, 2016; Sutherland et al., 2016
Agriculture	Experience of farmer	Sunny et al., 2022, Beckman and Xiarchos, 2013; Borchers et al., 2014; Li et al., 2021; Sutherland et al., 2016
Agriculture	Water depth	Agrawal and Jain, 2019
Policy and Politics	Subsidy and incentives	V. Kumar et al., 2020; Powell et al., 2021; Sunny et al., 2022,Agir et al., 2023; Beckman and Xiarchos, 2013; Ruiz-Fuensanta et al., 2019; Sutherland et al., 2016; Tate et al., 2012
Policy and Politics	Prior Adoption	Beckman and Xiarchos, 2013; Kata et al., 2021
Policy and Politics	Bureaucratic hurdles	Agir et al., 2023; Wagner et al., 2024
Policy and Politics	Co-ordination of agencies	Adhikari, 2020 Agir et al., 2023
Policy and Politics	Institutional setting governing and implementing policy	Agir et al., 2023
Policy and Politics	Ideological alignment of the government on the regional level	Dotti, 2016; Kleider et al., 2018
Economic	State economic resources	Authors analysis
Policy and Politics	Pilots pre-dating PM KUSUM	Authors analysis
Policy and Politics	Extra central financial assistance	Authors analysis

Table 3.1: Summary of findings from literature of factors identified closely co-relating to adoption of solar in agricultural context

Through the table 3.1 the most common themes identified which relate to adoption can be broken down into the socio-economic, agricultural, energy, policy related. In the subsequent sub-sections each of these themes are explored in more detail and identified factors are adopted to the state level.

3.1. Socio-economic

The economic factors can be broken down into macro-economic factors and micro-economic factors. Of the macro economic factors identified one of the key factors is the regional per capita income(Borchers et al., 2014). The regions with higher per income capita tend to see an uptick in adopting new technologies.In the micro economic factors identified for adoption of solar in agriculture and irrigation specifically, one of the most commonly mentioned factors influencing adoption is farmer incomes(Agir et al., 2023; Beckman and Xiarchos, 2013; Rana et al., 2021; Sutherland et al., 2016) . Most often this gives indication of the capital costs that can be borne by the farmers. The higher income farmers tend to be much more inclined to adopt as they have the ability to cover the capital costs associated with the technology. Another micro-economic factor which could most likely affect the ability of the farmer to adopt solar could be the existing farmer debt(Tate et al., 2012). Powell et al., 2021 and Wagner et al., 2024 also describe that risk tolerance of the farmer could play a role in the adoption of solar irrigation pumps in the study. The risk tolerance could be seen imperative to the outcomes observed as it could be argued that farmers who are indebted to a lower level tend to adopt more readily. Another factor which plays a role is the payback period of the installed technology for the farmer to adopt solar in their agricultural practices(V. Kumar et al., 2020; Moerkerken et al., 2023; Tate et al., 2012).

Of the social factors the most commonly identified factors are age and education level. Younger farmers are seen to adopt solar more often. Farmers with a higher education level tend to have higher adoption rates. Though, there could be rough approximations about the median age of the state or the literacy rate of the state, in the case of the current study it would be hard to discern the age of the farmers or the farmer literacy level on a state level. Another factor indicated is the internet access as it acts as a way to inform the farmers as well as a way for the farmer to be aware of the technology as well as policies to support solarization of agriculture(Beckman and Xiarchos, 2013; Borchers et al., 2014). Another often mentioned social aspect influencing adoption is awareness about technology, subsidies and policies. More aware farmers have a higher tendency to adopt. Again this factor could be influenced by multiple reasons like internet/ access to information, age, education etc., but individually as a factor it becomes harder to determine the metric which could best describe farmer awareness.

3.2. Energy

Factors in the domain of energy often play a role in the adoption of energy technologies. Beckman and Xiarchos, 2013 and Kata et al., 2021 both mention in their studies that the price of electricity/energy could play a role in the adoption of solar in agriculture. If the price of electricity is high then the farmers are more inclined to adopt solar energy as per their findings. Another factor mentioned is the energy consumed by farms(Ge et al., 2017). The higher energy consuming farms are inclined to adopt solar energy as it can be used to diversify the farm energy supply. Solar irradiation in the region is also seen as a possible factor influencing adoption(Ge et al., 2017). Though, in Schaffer and Düvelmeyer, 2016 it was noted that the solar irradiance did not play a role. Although it can be argued that the solar irradiance in the scope of the study of Schaffer and Düvelmeyer, 2016 does not tend to change drastically, as it is restricted to the region of Bavaria in Germany which might be a factor to take in into account in the context of India.

3.3. Agricultural

Farm and farmer characteristics often play a key role in the adoption of technology in the context of agriculture. Farm size held by the farmer is the aspect is cited most often in adoption of solar literature specific to agriculture(see table 3.1). Larger farm sizes are often associated with higher adoption rates. The type of farms is also identified as possible factors affecting the adoption. This varies from the diversification of the farms in terms of activities to the types of crops planted in the farm. Production specialization is also cited as one of the reasons to have negative effect on the willingness to adopt PV by farmers(Li et al., 2021). The identification of the type of farm or the crops planted would be tougher to ascertain in the context of state level as within the state there might be different types of farmers/crops grown. Though this aspect could be closely associated with the farm size and farmer incomes therefore acting as a closer approximation. Another possible consideration which could influence uptake of the technology, especially valid for solar powered water pumps, would be the ground water level(Agrawal and Jain, 2019).

Of the characteristics of the farmers, the factors most often mentioned is the farmer's experience (see table 3.1). Most often, the more experienced farmers tend to adopt solar less often. This factor, similar to age and education are best assessed in surveys on the farmer level while it would be harder to detect farmer experience statistics on the state level. Some studies also cited that if the farmer has embraced conservation practices or environmentally friendly practices, they often are more inclined to adopt solar pv as well(Beckman and Xiarchos, 2013).

3.4. Policy related factors which could influence outcomes

Policy support can be influential to adoption. Policy support and the awareness about the policy is seen as a possible reason for the adoption of policy on the farmer level(Beckman and Xiarchos, 2013; Sutherland et al., 2016; Wagner et al., 2024). Many researchers associate with the availability of Feed in tariffs[FiT] playing a key role in the uptake of solar in agriculture. Ruiz-Fuensanta et al., 2019 especially notes that the subsidies and grants provided by the regional or national governments play a key role in the adoption of solar in agricultural contexts by creating an artificial market pull.

To add to the factors identified, there are possible factors which are related the the way PM KUSUM is structured which have a strong influence on the outcomes observed on the state level(Table 3.1). One possible factor on the state level which could play a role in the adoption of the technology in the context of PM KUSUM could be the individual state budget. This state budget also seems to have a relation with the regional per capita incomes as states with higher per capita incomes tend to have higher state resources(Dev, 2024). As PM KUSUM is a demand based scheme and the respective state contributes 30 percent of the capital cost as subsidy through the scheme, the budget of the state could have an influence on the uptake. This is also posited through the observations of Reimer and Prokopy, 2014 who emphasize resource prioritization as an factor for policy outcomes on the state level.

Water depth and withdrawal rate is also a factor which should be considered as effecting the outcomes of the policy. Adhikari, 2020 mentions that the scheme discourages the setting up of solar water pumps in dark/grey zones of water availability unless it is proven to replace grid connected or diesel pumps. States and farmers who have already adopted solar in agricultural practices, could influence the further adoption of solar under the scheme(Beckman and Xiarchos, 2013; Kata et al., 2021). The presence of pilot programs before the implementation of PM KUSUM could be taken as a metric to identify if the adoption process has pre-dated PM KUSUM and what effect does it have on the adoption outcomes observed in the scheme. Agir et al., 2023 notes that the institutional setting is key to adoption of solar in agriculture as supported by Radulovic, 2005. The presence of a proper institutional setting is seen as a starting point for the effective implementation of policies.

The ideological alignment of the government on the regional level to the national level government could also play a role in the adoption of technology. If the government at the regional level is more inclined towards the political ideology of the national government it could be seen as a possible reasoning towards higher adoption rates as ideologically aligned governments tend to push harder with the policy(Dotti, 2016; Kleider et al., 2018). Agir et al., 2023 also notes that the co-ordination of agencies to play a role in the adoption numbers. Bureaucratic complexities is also seen as a hurdle to the adoption of solar and setting up of enterprises related to the field(Agir et al., 2023; Wagner et al., 2024).

4

Research Methodology

This chapter outlines the research methodology used to investigate the reasons behind the variation in performance of solar irrigation adoption. Section 4.1 introduces the mixed-methods approach employed in the study, detailing the rationale behind this methodological choice. Section 4.2 focuses on the Qualitative Comparative Analysis (QCA), providing an in-depth explanation of the method, the steps undertaken, the criteria for variable selection, and the operationalization of those variables. Following the discussion on QCA, Section 4.3 delves into the qualitative analysis. This includes the development of the questionnaire based on QCA findings, the process of conducting interviews, the selection criteria for the expert pool, and an explanation of the thematic analysis used to interpret the interview insights.

4.1. Research Approach

Effectively addressing the research question outlined in Chapter 1 required a carefully chosen methodological approach. As discussed in Section 1.2, previous studies evaluating policies in the domains of energy, agriculture, and solar irrigation have varied significantly in both methodology and scope. Evaluating the current policy requires a comprehensive understanding of factors driving policy outcomes and regional variations. Therefore, a mixed methods analysis was selected for its ability to integrate the strengths of quantitative and qualitative approaches, providing a multi-dimensional perspective relevant to this study.

The mixed methods approach aligned with the thesis goal of explaining why the outcomes of solar irrigation policies under PM KUSUM vary across states. The quantitative phase identifies broad patterns and tests relationships between variables (e.g., economic resources, policy implementation capacity, and irrigation demand), while the qualitative phase further explores contextual and on-ground factors which could give a better understanding of the results. Integrating these methods enhances reliability through triangulation and ensures both macro-level trends and micro-level nuances are addressed. The mixed-methods design is particularly suitable for multi-domain policies like PM KUSUM, as it captures economic, environmental, and socio-political dimensions, addressing both technological adoption and socio-economic impacts (Knickel et al., 2009).

Among mixed-methods designs, the explanatory sequential approach is the most suitable for this study, as it seeks to explain why and to what extent the policy is effective across different states (see Figure 4.1). This design begins with a quantitative phase, employing Qualitative Comparative Analysis (QCA) to identify configurations of factors influencing policy outcomes across regions. By accounting for the diverse contexts of Indian states, QCA helps explain variations in adoption rates through an analysis of regional differences.

The subsequent qualitative phase involves semi-structured interviews analyzed through thematic analysis to explore how the factors shape policy outcomes and refine the findings from the quantitative stage. Through the thematic analysis deeper insights into the solution configurations observed in the QCA is gained. This phase also delves into aspects such as implementation mechanisms, stakeholder roles, and inter-agency coordination, which are not fully captured in the quantitative phase. Additionally, qualitative insights are cross-referenced with QCA results to validate and enhance the robustness of the analysis (Greene et al., 1989).

While the explanatory sequential approach offers significant benefits, including a detailed understanding of regional variations, it is not without limitations, such as complexity, potential sampling issues, a longer timeline, and the possibility of subjective biases during the qualitative phase (Toyon, 2021). Despite these challenges, it provides a robust framework for comprehensively evaluating policy performance.

Ultimately, the mixed-methods approach directly supports the research objective by addressing the complexity and regional variability of solar irrigation policies in India. By minimizing biases associated with single-method studies and capturing diverse dimensions, it underscores its suitability for this study (Wipulanusat et al., 2020).

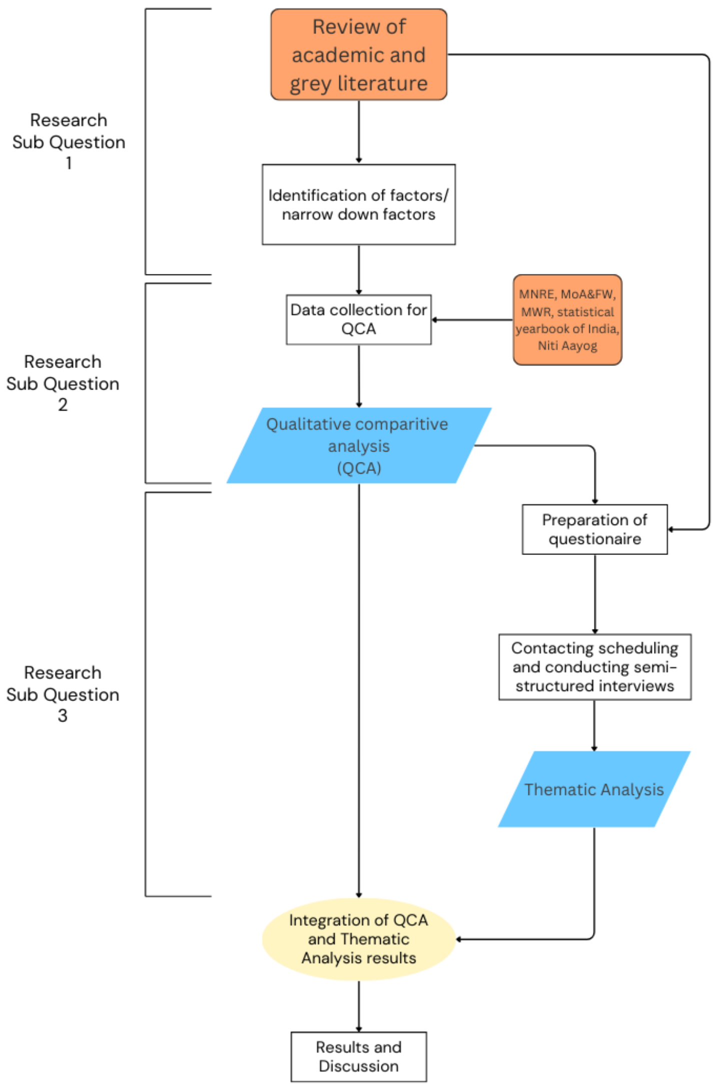

Figure 4.1: Mixed Methods Visual representation for Sequential - Explanatory Designs(Ivankova et al., 2006)

Before conducting the quantitative phase, it is crucial to identify the appropriate metric to distinguish well-performing from under-performing states. In this study, the chosen metric is the number of solar pumps installed as a percentage of the solar pumps sanctioned under Component B of the PM

KUSUM scheme, which serves as a proxy for evaluating state performance and reflects the resources allocated by state governments. It also accounts for state-specific factors such as size, population, irrigation needs, and the number of farmers impacted. The method employed for the quantitative analysis is Qualitative Comparative Analysis [QCA], which helps identify the factors most closely correlated with the adoption of solar technology in agriculture under the policy. These factors will be determined through a comprehensive review of academic and non-academic literature, focusing on common elements influencing the adoption of new energy technologies across the energy and agricultural sectors, as well as socio-economic indicators. The results of the QCA will provide a clearer understanding of the factors influencing policy outcomes and will inform the formulation of questions for the semi-structured interviews in the qualitative phase. By narrowing down the key factors and establishing possible causal links, QCA helped identify which factors were most likely to impact the adoption of solar irrigation technology under the policy, thus contributing to a more comprehensive analysis of policy performance.

4.2. Qualitative comparative analysis(QCA)

Qualitative Comparative Analysis (QCA) is a research method developed by Charles C. Ragin that combines qualitative and quantitative approaches to analyze cases. It is utilized for identifying patterns of causation across different cases by examining the relationships between various conditions and outcomes. As an asymmetric data analysis method, QCA amalgamates the empirical and logical intensity provided by qualitative approaches with quantitative metrics (Ragin, 1987). It employs set theory and boolean algebra to explore how combinations of set memberships affect outcomes(Federo, 2023). By analyzing the presence or absence of various conditions within a configuration, it identifies consistent patterns that influence the outcome of interest. Its analytical framework, rooted in three key principles(Federo, 2023): (1)Conjunction: independent causal conditions combine to produce an outcome; (2)Equifinality: different combinations of conditions could lead to an outcome; (3)Asymmetry: both presence or absence of the conditions can be associated with the outcome.

An advantage of using QCA is its ability to disentangle causal complexity (Federo, 2023). While QCA does not pinpoint a singular condition with the highest explanatory power, it effectively distinguishes between core attributes—those pivotal factors exerting substantial influence—and peripheral ones, which have a lesser impact (Federo, 2023). Unlike traditional social science methods constrained by ”net effects” reasoning, QCA explains outcomes through different combinations of causal conditions, allowing for a more nuanced understanding of how various factors interact. This enhances the current study by moving beyond a ”one size fits all” explanation, providing a deeper and more complex understanding of why positive or negative outcomes are observed across different contexts. Additionally, QCA is well-suited for studies with modest sample sizes, typically ranging from 5 to 50 cases (Ragin, 2007). Within this range, researchers often face too many cases to maintain detailed knowledge of each but not enough cases for conventional statistical methods to be applied effectively. Therefore, QCA strikes a balance, offering a powerful tool to analyze configurations of factors influencing policy outcomes.

QCA, grounded in set theory, distinguishes between two key types of causal conditions: necessity and sufficiency. A condition is considered necessary when the outcome is entirely encompassed within it, while it is deemed sufficient when the condition itself is entirely encompassed within the outcome. In QCA research, certain conditions may independently be insufficient but prove necessary for the outcome, while others might be unnecessary yet sufficient (Ragin, 2007).

Drawing from these principles, this study will utilize QCA to compare the adoption of solar water pumps in agricultural practices through the component B of PM KUSUM policy in India. The analysis will aim to uncover causal configurations that influence the outcomes of the PM KUSUM policy across the states in India. By deriving causal recipes from this examination, the research seeks to elucidate the intricate interplay between endogenous and exogenous factors, identifying the reasons for variations observed across states of the component B of PM KUSUM initiative.

4.2.1. Types of QCA

QCA is of three main types: Crisp set(csQCA), multi value(mvQCA) and fuzzy set(fsQCA). CsQCA was the initial type of QCA which was employed by Ragin, 1987 in their original analysis which is used to deal with complex sets of binary data. In crisp set QCA the input data are all metricized in binary form: 0 corresponding to the non membership of the condition or outcome and 1 corresponds to full membership of the condition or outcome(Pappas and Woodside, 2021).

As an extension of csQCA Cronqvist, 2004 developed mvQCA in which the condition or outcome could be a value of 0,1 or 2 to avoid the dichotomous nature of the analysis(Pappas and Woodside, 2021). In this method 0 corresponds to the absence of condition/outcome; 1 corresponds to partial membership of condition or outcome; while 2 corresponds to the full membership of conditions or outcomes. MvQCA upholds the concept of synthesizing datasets, where cases sharing identical outcomes are elucidated through solutions comprising variable combinations explaining a subset of cases with the same outcome. MvQCA has the potential to accommodate greater ambiguity in the determination of the presence or absence of outcomes or conditions. But in cases where definitions are less clear-cut, there remains a subset of cases that pose challenges in defining the extent of presence or absence.

Many QCA studies focus on crisp set methodology, though it comes with its fair share of scrutiny due to the dichotomous nature of input of variables(Ragin, 2007). FsQCA addresses the shortcomings of the csQCA approach by integrating set calibration methods. In FsQCA, conditions are assigned membership values ranging from 0.0 (non-membership) to 1.0 (full membership), with 0.5 serving as the crossover (Ragin, 2007). Through this method the raw data is calibrated such that the levels of memberships can be vary on degrees of membership. Through fsQCA when fuzzy logic principles combine with complexity theory the researchers are able to gain deeper and richer insight into the data(Pappas and Woodside, 2021). Pappas and Woodside, 2021 also mention that fsQCA is employed over cluster analysis as it has the ability to give explanations beyond which cases are more similar, core to cluster analysis, by identifying the different solution pathways that lead to the observed outcomes.

4.2.2. Limitations of fsQCA

The application of QCA methodology in policy analysis has existed for quite some time but the method does not come without its own set of limitations (Rihoux et al., 2011). Nonetheless, some scholars have critiqued its assumptions and relevance compared to traditional quantitative and qualitative research methods. Blackman et al., 2013 argues that judgment and interpretation of the researcher could play too much of a role in the results. Seawright, 2005 argued that QCA is less effective than quantitative research because it fails to address three key assumptions: the absence of a reliable testing tool for non-linear functional forms, the handling of missing variables, and the inherent implied causation. According to Seawright, 2005, QCA is considered less effective than traditional quantitative research due to its limitations in three critical areas: the lack of a dependable method for testing non-linear functional relationships, challenges in addressing missing variables, and the implicit assumption of causation. Furthermore, Tanner, 2014 asserted that policy research employing QCA, which functions within bounded sets and aligns measurements across various membership outcomes, is insufficient for revealing significant variations in outcomes.

Another critique of QCA pertains to data calibration. Parente and Federo, 2019 critique the growing trend where some QCA studies use data-specified calibration techniques like percentiles and rank orders, which deviate from best practices. They argue that while these techniques can be acceptable with transparency, they often lack the theoretical and substantive grounding needed for sound QCA-based research, raising concerns about subjectivity and sensitivity in the results. QCA has limited capacity to deal with different types of errors, though fuzzy-set analysis (fsQCA) can reduce the negative consequences of coding errors but may still be criticized for its high sensitivity to model specifications and inability to distinguish randomly assigned values from real data(Maggetti and Faur, 2013). FsQCA might give wrong results when variables have many descriptions, it can be hard to link causes to outcomes logically(Mendel and Korjani, 2013). Despite these criticisms, many scholars have strongly endorsed using not using QCA as a stand alone approach instead preferring to supplement it with other research methods.

4.2.3. FsQCA application

Before addressing the causal conditions and dependent variables including choosing the relevant variables, the respective datasets and operationalization of the variables for fsQCA this subsection will focus on the steps necessary to perform QCA. Pappas and Woodside, 2021 states that before performing fsQCA it is pivotal for the researcher to have a "workbench knowledge of both of the examined variables (conditions and outcome) as well as of the underlying theory and context." This knowledge will be used in data calibration, simplification of multiple solutions and interpretation of results. The process of fsQCA can be broken down into four basic steps: (1) Variable selection and dataset selection; (2) Calibration of datasets; (3) Truth table generation and generation of results; (4) Interpretation of results of fsQCA. Figure 4.2 describes the recommended steps to be taken for performing fsQCA analysis. This approach was adopted to our particular case and modified according to the needs of the current QCA.

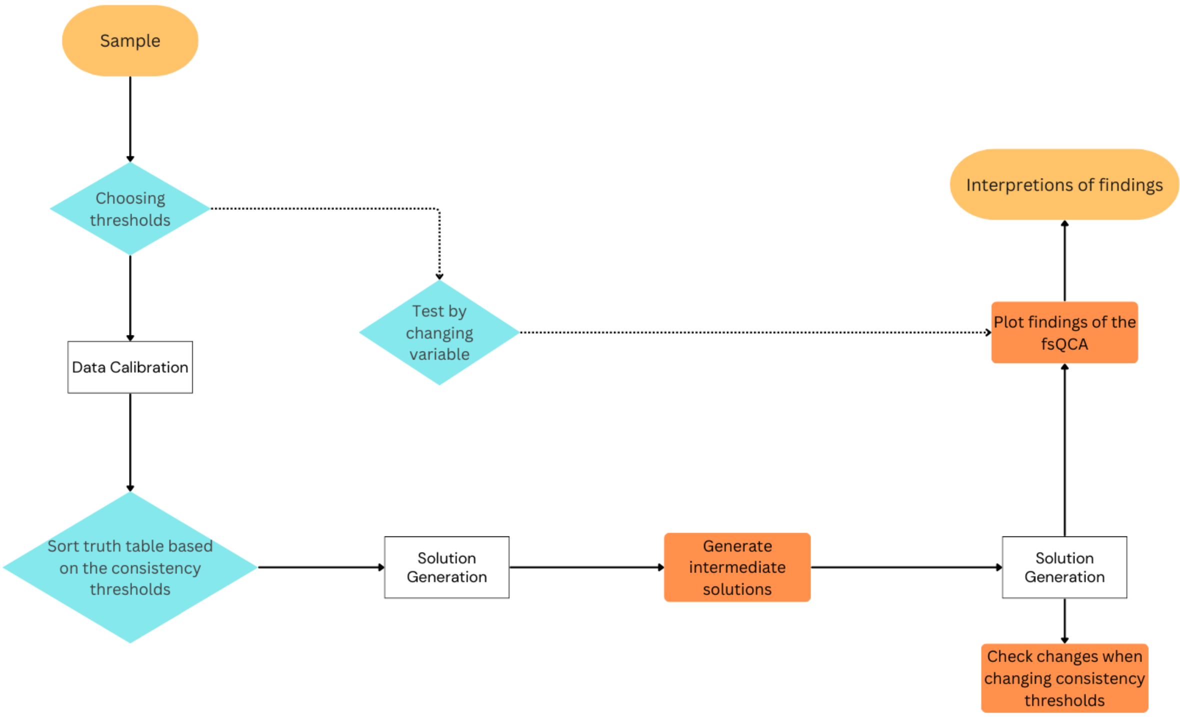

Figure 4.2: Recommended steps for fsQCA(Pappas and Woodside, 2021)

Variable and Dataset Selection

The first step in variable selection would be to identify the right variable to test as an outcome variable. This variable and the relevant dataset should ideally cover majority of the cases while providing a reasonable degree of representation of the desired outcome of the policy which is being tested. Pertinent to the current analysis the number of pumps installed as a percentage of number of pumps sanctioned in component B of PM KUSUM will be tested as the outcome variable. On the basis of the literature the initial set of variables that could be considered for fsQCA is obtained(see table 3.1). These prospective set of variables then has to be narrowed down to set of testable variables. To narrow down to a potential set of testable variables the first step is to identify the variables which are more likely to have an effect on the outcome observed. The variables which have limited or unavailable datasets are then discounted from the study to be addressed separately. Some variables which are complex and harder to discern quantitatively are also discounted from the current analysis. Some variables which have a strong affiliation with another prospective variable can be consolidated. Ultimately, the number of causal conditions are restricted to maintain a balance between complexity and interpretability for results. Post the selection of variable the datasets relevant to the variables should be selected and treated to remove the data points which have lower relevance to the outcomes and ones which can possibly skew the outcomes. The ideal dataset should accurately represent the condition which is tested and should account for the economic,size or demographic variations across the data points. Hence raw data needs to be normalized according to represent a consistent metric which is ready to be calibrated.

Calibration of Datasets

Once the causal conditions and dependent variables are selected and the datasets which represent the same are identified and normalized the next step is to transform the raw datasets into fuzzy sets with their values ranging from 0 to 1(Pappas and Woodside, 2021). The data points with a ”full” membership is represented as a score of 1 while a data point ”no” membership is represented with a score of 0 while the points which are at the crossover point of 0.5 are at the ”intermediate” level of membership. Data calibration could be of two kinds: Direct calibration and indirect calibration. In direct calibration three quantitative break points of the datasets have to be determined by the researcher. These break points represent the points which indicate fully in, intermediate and fully out levels of membership. In the indirect method the membership levels can be re-scaled according to the knowledge and theoretical substantiation by the researcher. The direct method is recommended more often to be used as it can lead to more rigorous studies with replicable and easy to validate results(Pappas and Woodside, 2021). Choosing the right thresholds for calibration into fuzzy sets is important as the type of datasets have a bearing the assignment of the value from 0-1 in the calibrated dataset and ultimately the results of QCA.

For that end, the calibration of datasets are done with the reference of the suggestions made by Pappas and Woodside, 2021 in their guide to perform fsQCA(refer table 4.1). Through the process of calibration all the value are placed into a log-odds metric curve ranging from 0 to 1. Parente and Federo, 2019 critique the use of data-driven calibration techniques like rank orders and percentiles in QCA, arguing that they often lack the theoretical grounding needed for robust research and can introduce subjectivity. This study acknowledges this shortfall in relying on rank orders and percentiles for calibration thresholds. Given the absence of strong theoretical cut-off points for many of the datasets chosen, this study’s approach follows the recommendations of Pappas and Woodside, 2021 to set the calibration thresholds of the datasets. For datasets which are distributed normally the calibration thresholds are set at 95th percentile for inclusion,50th percentile for crossover point and 5th percentile for exclusion threshold. The datasets which are skewed either towards left or right on the distribution the thresholds are set at 80th percentile, 50th percentile and 20th percentile as inclusion, crossover and exclusion thresholds respectively. For datasets represented in 7-point likert scales the thresholds are set at 6, 4 and 2, and for datasets which are represented in 5 point likert scales the thresholds are 4, 3 and 2. Setting the calibration breakpoints at 0 or 1 is not possible as the two membership scores coincide to positive and negative infinity in the lograthmic odds curve(Ragin, 2008b). The cases that are exactly at 0.5 (intermediate set membership) there would be an ambiguity present with the outcome and the influence of the variable on the outcome. Fiss, 2011 suggested that to overcome the ambiguity in intermediate set memberships a constant of 0.001 could be added to the calibrated dataset.

Dataset type	Inclusion threshold	Crossover threshold	Exclusion threshold
Normal distribution	95th percentile	50th percentile	5th percentile
Skewed distribution (left or right)	80th percentile	50th percentile	20th percentile
5-point likert scale	4	3	2
7-point likert scale	6	4	2

Table 4.1: Calibration thresholds recommended by Pappas and Woodside, 2021

Truth table and result generation

As the datasets are calibrated now the truth table has to be generated using the data analysis software. In the case of this particular study QCA is performed using the fsQCA software developed by Charles C Ragin(Ragin, 2008a). It is important to decide the consistency threshold. Consistency measures how well the empirical data conform to a hypothesized relationship, indicating the reliability of a condition or combination of conditions in predicting an outcome (Ragin, 2008a). The consistency threshold is to be set at a minimum of 0.75 as recommended by (Rihoux and Ragin, 2009), meaning a condition should predict the outcome correctly in at least 75% of cases to be considered reliable based on the dataset which is provided. Once this threshold is set then the truth table can be generated in the software. The cases which correspond to no outcomes are discounted from the truth table which is generated. This table gives an indication on weather the presence or absence of condition will lead to the positive or negative outcomes based on the data input which is provided. Is it necessary to set a proper consistency threshold as a low consistency threshold though could lead to a reduction of type II errors(false negatives) but lead to an increase in type I errors (false positives)(Pappas and Woodside, 2021). For this study the the consistency threshold of 0.8 is employed as recommend in the the QCA studies prior but in some simulations when the outputs are not present the consistency threshold may be lowered to 0.75(the minimum recommenced threshold by Rihoux and Ragin, 2009)(Pappas and Woodside, 2021)

Once the truth table is generated the solutions of the possible configurations leading to an outcome can be generated. The solutions can be of three types: complex, intermediate and parsimonious solutions. Complex solutions consider all possible causal combinations without simplification, retaining every detail of the data(Ragin, 1987). Parsimonious solutions use logical minimization to include only the most essential causal conditions, sometimes ignoring less supported configurations(Ragin, 2008a). Intermediate solutions balance complexity and simplicity by including only plausible causal conditions based on theoretical and substantive knowledge. This makes intermediate solutions the pertinent configurations to be studied in the current analysis.

Interpretation of Results

Once the intermediate solutions are generated, the configurational mixes which lead outcomes which have the consistency above the consistency threshold set are visualized in a tabular format which indicates the weather the presence or absence of a variable would lead to the outcome observed. Using this the analysis, the researcher can discern the possible configurations that lead to the outcomes observed and report on the same.

4.2.4. Dependent Variable - Outcomes of PM KUSUM scheme

The outcome variable chosen for the qualitative comparative analysis (QCA) is the percentage of installed solar pumps relative to the sanctioned solar pumps under Component B of the PM KUSUM scheme. This component aims to replace diesel irrigation pumps with solar-powered alternatives, contributing to the ”de-dieselization” of agricultural irrigation. Given the focus on solarization, the factors influencing outcomes will vary depending on the unique context of each state, including its resource allocation, irrigation demand, size, population, and the farmers targeted by the scheme. To capture these differences, the percentage of installed pumps against sanctioned pumps serves as the outcome variable.

The data for Component B outcomes, as of September 30, 2024, were sourced from the PM KUSUM website. The normalized outcomes for each state are presented in Table 5.1. Union territories, except Jammu & Kashmir, were excluded from the analysis due to a lack of data on sanctioned quantities. Similarly, Andhra Pradesh and Sikkim were excluded because of lack of outcome data. Additionally, Ladakh was excluded due to the absence of reliable data on factors influencing solar pump installations.

4.2.5. Causal conditions - Factors which influence outcomes

As identified in chapter 3 there are many factors which can be identified pointing towards the adoption of solar in agricultural practices. These can be varied in nature and spanning different domains like socio-economic, energy, agricultural and policy related. Though all these factors could have an influence on the adoption of solar in the context of state level outcomes in India, for the purposes of the current study the factors would be narrowed down to some relevant factors which could be key to this particular study. A summary of the factors which are considered for the QCA part of the study are shown in the table with the reasons for selection or non selection for the qualitative comparative analysis om table 4.2.

Factor Type	Factor	Inclusion/exclusion, reason for non-inclusion
Economic	Regional Per capita income	Yes
Economic	Farmer incomes	Yes
Economic	Farmer debt	No, It can be accounted for to an extent under the farmer incomes as the higher income farmers tend to be less under the pressure of debt
Economic	Capital costs for installed technology	No, Capital costs would not tend to vary significantly across states
Economic	Payback period for installed technology	No, Payback period is dependent on multiple variables like feed-in-tariffs/rate of energy purchase, energy consumption of farm, irradiation levels of region
Economic	Individual state budgets	No, It can be to an extent accounted for in the GSDP per capita(Dev, 2024)
Social	Age of farmer	No, dataset not available
Social	Education level of farmer	No, dataset not available
Social	Internet access of farmer	No, dataset not available
Social	Awareness of farmer	No, subjective and harder to discern without farmer level data
Energy	Cost of electricity/diesel	No, as the cost of electricity/diesel for agricultural use is subsidized across multiple states
Energy	Energy demand of the farm	No, primarily relevant for component C
Energy	Solar irradiation of the region	No, the solar irradiation across India is on the higher end as it is closer to the equator making most of India conducive for solar installations
Agriculture	Size of farm/land available	No, It is not counted as an causal condition as some aspects of the land size holdings are incorporated under farmer incomes and some aspects are accounted for under irrigation demand
Agriculture	Cropping practices/type of farm	No, accounted for in farm incomes and irrigation requirements
Agriculture	Annual irrigation draft	Yes
Policy/political contexts	Prior adoption	Yes
Policy/political contexts	Alignment of regional government with national government on ideological level	Yes
Policy/ political contexts	Institutional setting	No, too difficult to discern effectively
Policy/ political contexts	Policy mechanisms	No, too difficult to discern effectively
Policy/political contexts	Co-ordination of agencies responsible for implementation	No, too difficult to discern effectively
Policy/political contexts	Subsidy for energy	No, Electricity subsidy data is limited to 17 states, as the subsidy amounts for agriculture in other states and union territories remain unclear(Aggarwal et al., 2020)

Table 4.2: Factors Type, Factor and their consideration or non consideration for QCA

Borchers et al., 2014 identified regional per capita income as a possible factor influencing the adoption rates of renewable energy technologies on a regional level. GSDP per capita could be used as an indicator incorporating per capita incomes, to determine whether a region is economically well-off or not, also reflecting the state-level resources to some extent (Dev, 2024). Farmer incomes and debt levels at the regional level could play a more pronounced role in determining whether a farmer can cover the capital costs and repay any loans availed through schemes to cover these costs (Powell et al., 2021; Tate et al., 2012). In this case, farmer incomes are considered the metric to be studied, as higher-income farmers tend not to be under the pressure of debt (Grzelak, 2022; A. Kumar and Saroj, 2019). The capital costs associated with setting up solar installations are assumed to not vary across states, as there are no additional state-level tariffs that could cause regional variations. On the other hand, the payback period depends on many factors, such as the cost of energy sold, the amount of energy consumed for irrigation, the capital cost, and the irradiation levels of the region, making it more complicated to discern at the regional level. Hence, it will not be included as a variable in the current study.

Many studies cite social factors such as age, education level, and internet access of the farmer as indicators of adoption rates. Education level is positively related to internet engagement, and high internet engagement is strongly associated with an individual's knowledge levels and awareness (Lee, 2009). However, most studies indicating age, education, and internet access as key factors in adoption levels are based on farmer-level surveys. In the current study, there is no concrete data available for average farmer age, education levels of farmers, or internet access of farmers. Rough approximations such as state-wise literacy rates, rural internet access, or the average age of rural populations are available, but these datasets are not specific to agricultural practitioners. Hence, these factors are not included in the current analysis. If datasets for age, education, and internet access were available at the farmer level, there would be a stronger argument to include them in the QCA study.

Energy costs play a role in adoption, as higher energy costs prior to the installation of solar energy are seen as driving factors for renewable energy adoption, as noted by Kata et al., 2021 and Beckman and Xiarchos, 2013 in their respective studies. In the case of India, electricity and diesel provided for agricultural purposes are often subsidized or even free in many states. However, the reporting of the subsidy disbursed for agricultural purposes is limited to a dataset containing 17 of the 36 states and union territories (Aggarwal et al., 2020). While this dataset is available, it could limit the study to only 17 states, and hence it is not considered a variable for testing in the QCA. Another factor that could influence adoption is the farm's energy demand, which often depends on farm size and crop type, reflecting irrigation requirements. Larger farms and certain crops with higher irrigation demands tend to have greater energy needs. To account for farmland size in the irrigation requirements, the net area sown in each state is used to calculate the annual irrigation requirements for states in India. The metric used to represent irrigation requirements powered by pumps is the annual groundwater irrigation draft divided by the net area sown in the state.

In the case of solar adoption, it is critical to consider the potential solar irradiation that can be harnessed from the area, as this factor could be pivotal to the farmer's decision. Solar irradiation heavily influences the payback period of a project or irrigation pump. In peninsular India, irradiation levels are generally high enough to make economic sense for utilizing the abundant solar resource, and thus, solar irradiation is not included as a variable in this study (SolarGIS, 2011). However, it could be a relevant factor to consider in subsequent studies of a similar nature. While farm cropping practices could affect irrigation demand, this is accounted for in the annual irrigation draft.

Individual state budgets could impact the availability of funds for sanctioning solar installations. However, other factors could influence state budgets and their ability to sanction funds for PM KUSUM, including the resource prioritization of the state government and its mandates. To some extent, this is accounted for by GSDP per capita, which helps distinguish economically well-performing states from those that are not.

Pioneer states often have higher adoption rates following the implementation of a new renewable energy policy or scheme. In this particular study, the prior adoption of solar energy in the electricity mix across different states of India preceding the implementation of PM KUSUM will be tested to see whether this hypothesis holds. The chosen metric is the renewable purchase obligations (RPO) met by each state through solar energy for the financial year 2018-19. Additionally, the institutional setting, policy mechanisms, and their effect on the scheme's implementation and agency coordination are hard to metricize in the QCA. Regional government alignment with the central government on an ideological level could prove to be a factor for a more harmonized deployment of the scheme at the state level, as it may drive the objectives of state governments. To test this hypothesis, a factor of alignment during the period of the scheme's implementation will be included in the QCA analysis.

An alternative variable to indicate irrigation demand could have been the number of diesel pump sets in Indian states. This metric could serve as a proxy for irrigation pump demand, particularly in regions where farmers are motivated to replace existing diesel pump sets. However, this variable was not selected for the study as it does not account for farmers who might be interested in solar pump sets due to unreliable electricity access for irrigation.

The variables selected to evaluate the positive and negative performance of Component B of the PM KUSUM scheme are summarized in Table 4.3. These include GSDP per capita, which serves as a proxy for the economic resources of the state and reflects the region's financial capacity, and farmers' monthly income, indicating their ability to bear capital costs. The annual groundwater irrigation draft is included to represent the regional demand for irrigation, while solar RPO compliance prior to the scheme's implementation reflects the general level of solar adoption in the region. Finally, the ideological alignment between the regional and national governments is considered, capturing whether the state and national governments belong to the same party or coalition throughout the scheme's duration and examining its potential influence on policy implementation. Together, these variables provide a robust framework for analyzing the factors influencing policy performance.

Factor Type and Factor Identified	**Dataset Selected**	**Data Source**	**Year & Frequency of Collection**
Micro Economic, Regional per capita income	GSDP per capita in $	Reserve Bank of India(RBI, 2022)	2022; every year
Micro Economic, Farmer income	Average farmer income in Rs.	MOSPI, India(77th National Sampling Survey)(NSO, 2019)	2019; every 8-10 years
Agriculture, Water withdrawal rates	Annual groundwater irrigation draft in bcm.	Ministry of Jal Shakti(Shakti, 2020)	2020; every 3 years
Agriculture, Area sown	Net Area Sown in Ha	Agricultural census(MoA&FW, 2023)	2015-16; every 5 years
Policy, solar adoption prior to KUSUM	Solar RPO as a percentage of electricity demand in FY 18-19	Niti Aayog Dashboard(Aayog, 2024	2018-19, Yearly
Political, Ideological alignment of regional level government	Weather state level government is aligned with national level government over the period of 2019-2023	Grey literature	2023; from 2019-23

Table 4.3: Factors, data selected, data source, Year and Frequency of Data collection (All data is collected state wise)

4.2.6. Operationalization of Dependent Variables

In this section the operationalization of the dependent variables for component B of the PM KUSUM scheme is described with all the key decisions taken for operationalization stated.

Component B - Installed pumps/sanctioned pumps(%)
The outcome for fsQCA analysis which is considered for the current study for component B of PM KUSUM is the number of installed pumps as a percentage of number of sanctioned pumps. The data source for the installed and sanctioned solar pumps is the PM KUSUM website which has updated the sanctioned quantity per state for different states of India until 30 September 2024(MNRE, 2019). The dataset is then plotted and the data is found to be "left skewed" distribution as depicted in figure B.1. Referring to the suggestions made by Pappas and Woodside, 2021 as seen in table 4.1 the thresholds are set at 80th, 50th and 20th percentile for the full membership, intermediate and non membership values to form a log-odds curve. The states which have not adopted the component to implement i.e. sanctioned quantity is zero is excluded from the study(Bihar). The final calibrated dataset is as seen in figure 4.3.

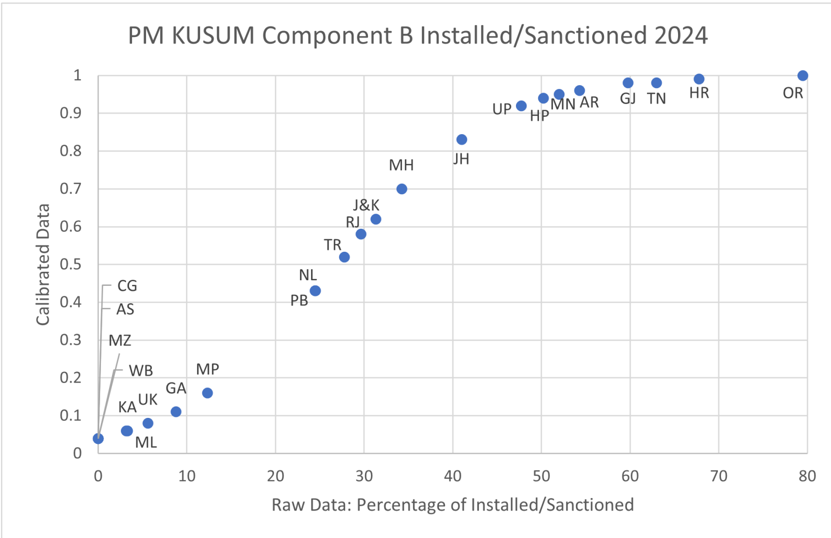

Figure 4.3: Component B sanctioned pumps per net area sown calibration

4.2.7. Operationalization of causal conditions

In this section the operationalization of the causal conditions for component B of the PM KUSUM scheme is described with all the key decisions taken for operationalization stated. In this section the factors are narrowed down to the factors which are relevant to the current study as discussed in the section 4.2.5. These factors are described in table 4.3. The calibration set points are mentioned in the table 4.4.

Variable	Dataset Notation	Distribution type	Inclusion threshold	Crossover threshold	Exclusion threshold
Installed /Sanctioned (%)	INSB	Left Skewed	80th percentile - 53	50th percentile - 27	20th percentile - 1
Farmers Monthly income	FMI	Left Skewed	80th percentile - 18836	50th percentile - 11924	20th percentile - 8551
GSDP per capita	GSDP	Left Skewed	80th percentile - 3564	50th percentile - 1985	20th percentile - 1561
Ideological alignment of state govt. with national govt.	ALI	Right skewed	80th percentile - 5	50th percentile - 4	20th percentile - 0
Annual irrigation draft per net area sown	AID	Left Skewed	80th percentile - 1905	50th percentile - 838	20th percentile - 86

Solar RPO as of FY 18-19	RPO	Left Skewed	80th percentile - 3.5	50th Percentile - 0.6	20th Percentile - 0.01

Table 4.4: Causal Conditions and Corresponding Dataset Notations, Distribution Types, and Thresholds(in percentiles and numbers)

Regional Per capita Income

The indicator for regional per capita income can be captured by the GSDP per capita of the region for every state of India. For fsQCA analysis this is then operationalized to fit the log-odds curve. The data source for the GSDP per capita is the Reserve Bank of India Yearbook of Statistics every year(RBI, 2022). The sample size chosen for the collection is representative of the per capita income in the state hence there is no need for normalization for the data series(GSDP per capita). The dataset is then plotted and the data is found to be ”left skewed” distribution as depicted in figure B.3. Referring to the suggestions made by Pappas and Woodside, 2021 as seen in table 4.1 the thresholds are set at 80th, 50th and 20th percentile for the full membership, intermediate and non membership values to form a log-odds curve. The operationalized variable is then tested for component B of PM KUSUM in QCA analysis. The final calibrated dataset is as seen in figure 4.4.

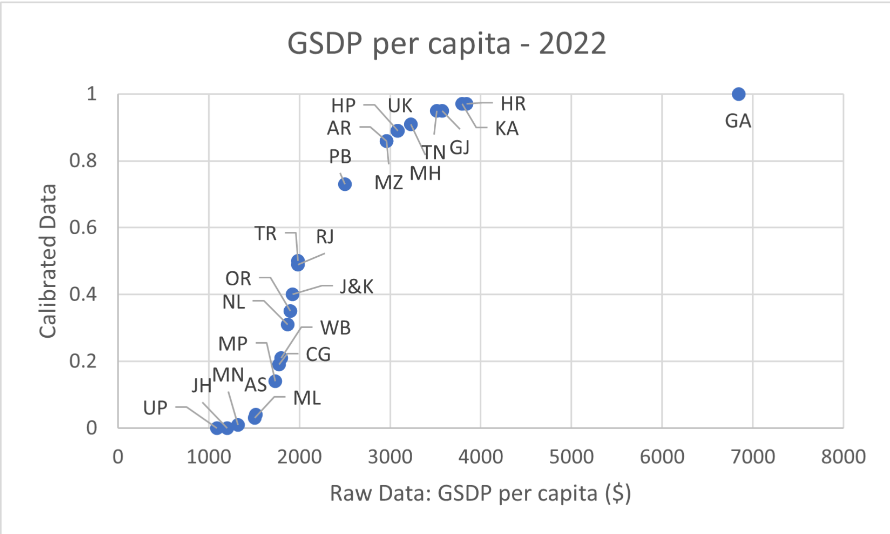

Figure 4.4: GSDP per capita calibration

Farmers Monthly Income

The indicator for ability to purchase for farmers can be captured by the average monthly income of farmers for every state of India. For fsQCA analysis this is then operationalized to fit the log-odds curve. The data source for the farmers incomes is the ministry of statistics and program implementation’s 77th national sampling survey which is collected every 8 to 10 years . The sample size chosen for the collection is representative of the farmers in the state hence there is no need for normalization for the data series(farmer income). The dataset is then plotted and the data is found to be ”left skewed” distribution as depicted in figure B.2. Referring to the suggestions made by Pappas and Woodside, 2021 as seen in table 4.1 the thresholds are set at 80th, 50th and 20th percentile for the full membership, intermediate and non membership values to form a log-odds curve. The operationalized variable is then tested for component B of PM KUSUM in QCA analysis. The final calibrated dataset is as seen in figure 4.5.

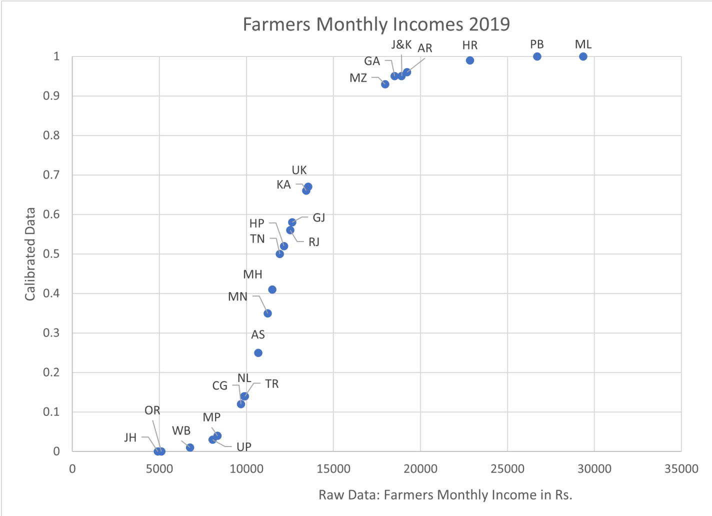

Figure 4.5: Farmers monthly incomes calibration

Annual Irrigation Draft

The indicator for water withdrawal rates indicating the irrigation demand, can be captured using the annual groundwater irrigation draft. This metric is normalized over the net area sown to capture the addressable area for every state in India. For fsQCA analysis this is then operationalized to fit the log-odds curve.The data source for the annual irrigation draft is collected from Ministry of Jal Shakti's dashboard for the year 2020 which has datasets for every three years(Shakti, 2020). The dataset is then plotted and the data is found to be "left skewed" distribution as depicted in figure B.5. Referring to the suggestions made by Pappas and Woodside, 2021 as seen in table 4.1 the thresholds are set at 80th, 50th and 20th percentile for the full membership, intermediate and non membership values to form a log-odds curve. The operationalized variable is then tested for components B in QCA analysis. The final calibrated dataset is as seen in figure 4.6.

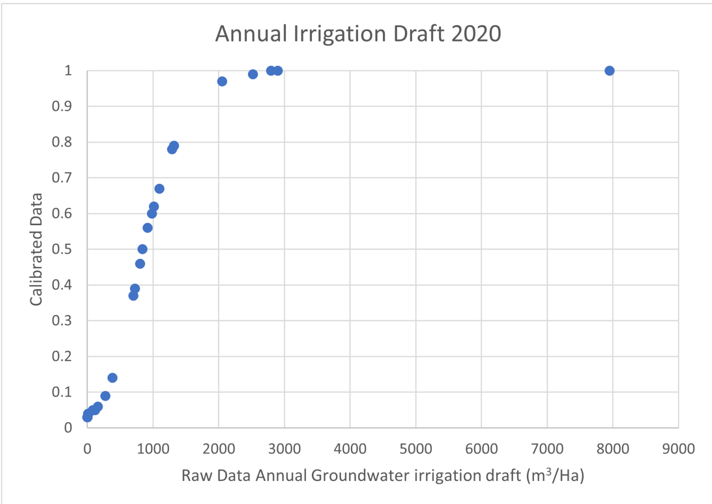

Figure 4.6: Annual irrigation draft per net area sown calibration

Prior adoption of Solar

The indicator for prior adoption practices in states can be captured by seeing which states have had interest in promoting solar. The metric which closely resembles the same is the solar renewable purchase obligation percentages achieved in the year preceding implementation of PM KUSUM(Aayog, 2024). For fsQCA analysis this is then operationalized to fit the log-odds curve.The dataset is then plotted and the data is found to be "left skewed" distribution as depicted in figure B.4. Referring to the suggestions made by Pappas and Woodside, 2021 as seen in table 4.1 the thresholds are set at 80th, 50th and 20th percentile for the full membership, intermediate and non membership values to form a log-odds curve. The operationalized variable is then tested for components B in QCA analysis. The final calibrated dataset is as seen in figure 4.7.

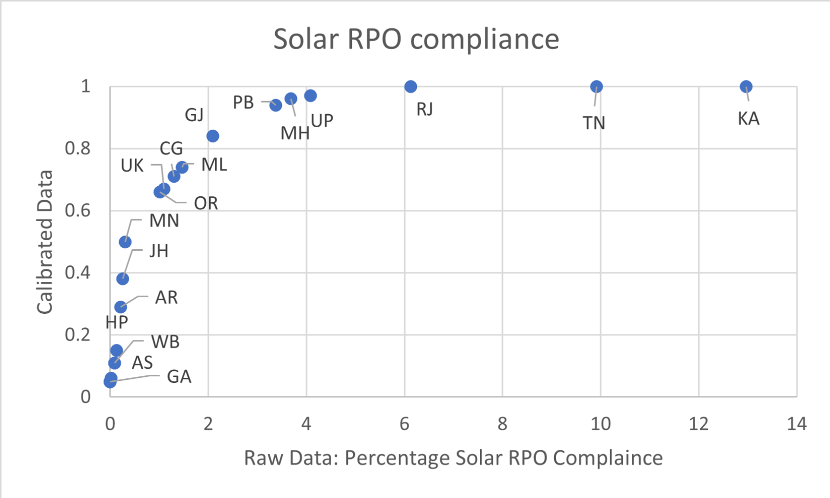

Figure 4.7: Solar RPO percentages calibration

Ideological alignment of national and regional government

The indicator for ideological alignment of national and regional governments can be captured by seeing the number of years the state level government is ideologically in the same coalition or same party as the national level government. The time period selected for this is from March 2019, when the scheme was launched to March 2024(5 Years). For fsQCA analysis this is then operationalized to fit the log-odds curve.The data source for the same is collection through news sources and the government websites. The dataset is then plotted and the data is found to be ”right skewed” distribution as depicted in figure B.6. Referring to the suggestions made by Pappas and Woodside, 2021 as seen in table 4.1 the thresholds are set at 80th, 50th and 20th percentile for the full membership, intermediate and non membership values to form a log-odds curve. The operationalized variable is then tested for components B and C in QCA analysis. The final calibrated dataset is as seen in figure 4.8.

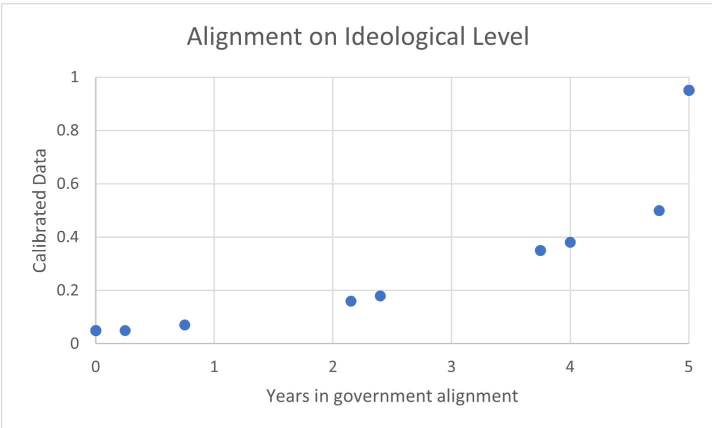

Figure 4.8: Ideological alignment of national and regional government calibration

4.2.8. Validity and Reliability

Validity of a research represents the rigor of the research complemented by the high quality of research(Creswell, 2014). There are two main types of validity which have to be kept in mind when describing the validity of the research in the current context: internal validity which refers to the degree to which the observed effects in the study are due to the experimental manipulation rather than other factors while external validity refers to the extent to which the findings of a study could be generalized beyond the specific conditions of the study to other study settings(Campbell and Stanley, 1963). This study ensures internal validity by performing robustness checks on the results of the thesis to see how the consistency thresholds changing have an effect on the outcomes observed while also replacing one condition to see weather it changes the results of the QCA significantly. Another way to validate the analysis by the QCA is to check the findings with the qualitative results of the thesis. The results of the thesis and the methodology could also be applicable to similar studies which explores the regional differences in the performance of a particular policy with appropriate adjustments made to the variables tested in the QCA to accommodate the particular context which is being studied. This ensures the external validity of the thesis.

4.3. Qualitative Analysis

The qualitative aspect of the research focuses on ”collecting and analyzing descriptive, non-numerical data to understand complex human behavior, experiences, and social phenomena” (Lab, 2024). Unlike quantitative research, which relies on statistical data to explain the researched topic, qualitative methods delve into non-numerical data derived from interviews, focus groups, or observations made by the researcher to explain the reasoning and motivations driving social phenomena or human behavior (Denzin and Lincoln, 2005). The key elements of qualitative analysis include subjectivity, contextual development, and the rich, narrative nature of the data (Kvale, 1996). This type of research also could be used as a complementary research method to quantitative aspects. This approach helps to develop a deeper understanding of the research question. Additionally, qualitative research can also complement quantitative methods, creating feedback loops that refine the study further by allowing insights developed in one phase to inform the results of the other (Greene et al., 1989).

Semi-structured interviews were selected as the primary data collection method for this research due to their ability to offer both structure and flexibility (Kvale, 1996). This approach allows for focused discussions on predetermined themes while enabling respondents to introduce relevant insights that might not have been anticipated. Such flexibility is particularly valuable when examining complex and multi-dimensional topics, such as state-level variations in policy implementation (Kallio et al., 2016). To analyze the insights gained, thematic analysis was chosen for its capacity to systematically identify, organize, and interpret patterns or themes within the data (Braun and Clarke, 2006). This method is particularly well-suited for qualitative research, allowing the identification of recurring themes that reflect the nuances of the interviewees' perspectives, making it ideal for exploring the intricacies of policy implementation across different contexts.

4.3.1. Semi-structured interview

The method used to interview the prospective key individuals for this phase of the research is semi-structured interviews. Semi structured interviews is a qualitative data collection method which combines a set of pre determined questions with the flexibility of exploring new topics which arise in natural conversation(Kvale, 1996). This method with the structured guideline helps set up the discussion while giving possible room for additional insights on points raised in the earlier phases of the interview to gain a better understanding based on interviewees responses. The semi-structured interviews give the flexibility and depth to the topic discussed by giving the interviewer an opportunity to explore unexpected insights by allowing follow-up questions being ideal for topics which require an understanding of subjective experiences(Galletta, 2013). Semi-structured interviews allows the researcher to maintain balance between the issues that they wish to gain more insights about with the issues that seem important to the interviewee. Semi-structured interviews provide greater flexibility than structured ones, allowing room for exploration while maintaining more focus and direction than open-ended interviews, preventing conversations from drifting and ensuring key topics are addressed.(DiCicco-Bloom and Crabtree, 2006).

4.3.2. Expert Pool Selection and Interview Process

To gain a comprehensive understanding of the implementation of Component B of the PM-KUSUM scheme, a series of semi-structured interviews was conducted with experts and key stakeholders. The selection of experts was primarily based on their involvement in the field, as reflected in articles, reports, and policy briefs published by leading think tanks in India. Their insights were instrumental in shaping the analysis. After identifying suitable candidates, their contact information was sourced through publicly available resources. In total, around 40 experts and relevant members key to the policy were contacted, out of which 9 participants agreed to participate in the interviews. The roles, involvement and occupational details of the participants are mentioned in appendix C. Attempts to reach out to key individuals of the Ministry of New and Renewable Energy (MNRE) to gain their insights on the policy were made but were unsuccessful. The key actors were approached via email, inviting them to participate in the interviews. Upon their agreement, interviews were conducted either in person or virtually, depending on logistical feasibility and participant preferences.

During the interviews, data was collected in the form of transcripts, audio, and video recordings, all managed in compliance with GDPR regulations. Personal information, including the identities of participants, has been anonymized and will be destroyed upon the conclusion of this research to ensure confidentiality. These interviews provided critical insights into why certain states perform better in the implementation of Component B, while others lag behind. The findings from the interviews help understand the outcomes of the qualitative comparative analysis, allowing for a deeper exploration of state-level variations.

4.3.3. Interview outline

The interviews with experts from think tanks and academia are designed to gather comprehensive insights into the disparities in the implementation of Component B of the PM KUSUM scheme, overseen by the Ministry of New and Renewable Energy (MNRE). The development of the initial questionnaire was guided by the findings of the qualitative comparative analysis (QCA), which identified key themes in economics, politics, and agriculture. Furthermore, insights from both academic and non-academic literature emphasized the importance of institutions, implementation mechanisms, and the role of stakeholders in influencing the effectiveness of the policy. These discussions aim to uncover the underlying reasons behind the significant variation in state-level performance, with a particular focus on how economic, political, and physical factors identified in the QCA shape outcomes. By examining these aspects, the interviews help explain why certain states have been more effective in implementing the scheme and provide an opportunity to delve deeper into the QCA results.

In addition, the interviews explore how the level of autonomy granted to states in executing the scheme contributes to the variability in strategies and approaches, further influencing the overall effectiveness of the program. The discussions also address broader challenges faced by states in achieving the MNRE's de-dieselization target.

Since the interviews are semi-structured in nature, they provide the flexibility to explore topics that emerge organically during the discussions. This approach allows for deeper insights into unanticipated issues or perspectives that may not have been initially considered. The detailed questionnaire will be included in the appendix C of the thesis.

4.3.4. Thematic analysis

Thematic analysis (TA) is a widely used method for analyzing qualitative data, particularly in semi-structured interviews, due to its flexibility and ability to provide rich insights into research question. TA allows researchers to identify, analyze, and report themes or patterns within data, offering both inductive (data-driven) and deductive (theory-driven) approaches (Braun and Clarke, 2006). Inductive analysis is data-driven, where themes emerge directly from the data without prior expectations, while deductive analysis is theory-driven, relying on predefined codes based on existing theory or literature (Fereday and Muir-Cochrane, 2006). This method enables researchers to explore semantic content, (focusing on the words said as is) as well as latent themes (underlying meaning of the statements made) making it suitable for complex datasets (Clarke and Braun, 2014). One of its key advantages is its adaptability to various research paradigms, providing a systematic way to interpret findings and highlight relationships between themes. TA is particularly valuable for capturing nuances in interview data, which is essential in understanding diverse perspectives (Nowell et al., 2017).

For this research, an inductive approach was chosen to interpret the findings from expert interviews.

This approach allows for the identification of both latent (underlying) and semantic (explicit) themes from the responses. Coding was done iteratively, with the possibility of refining or adding codes as new insights emerge during the analysis. This flexibility ensures the rigor of the coding process, as ongoing revisions help capture the complexity of interview data. Thematic analysis' ability to accommodate emerging themes and its iterative nature make it an ideal method for exploring the nuanced factors influencing the implementation of Component B of the PM-KUSUM scheme.

4.3.5. Limitations of semi-structured interviews and thematic analysis

While these methods for collection of data and analysis present many strengths it do not come without their own set of limitations. Semi-structured interviews may be a time consuming process especially with the process of development of questions, finding a representative set of participants, trying to ensure diversity of participants and contacting and scheduling of interviews(DeJonckheere and Vaughn, 2019). This method of data collection could also be susceptible to interviewers or interviewees subjective biases which could bleed into the study(Irvine et al., 2013). The conversational text once collected will be very rich and complex hence needs to be handled very diligently requiring researcher to be thorough.

Paoli, 2023 in their assessment of thematic analysis state dependence on human interpretation for the development of themes, and the subjective nature of development of theme making it difficult to reproduce as limitations of thematic analysis. Braun and Clarke, 2006 cite the lack of clear boundary setting as a possible hindrance to thematic analysis. Similar to semi-structured interviews subjective biases could have a bearing on the outcomes of the analysis(Clarke and Braun, 2017). Though these limitations could have a significant bearing on the overall research, some of these factors could be controlled by trying to limit subjective biases, while maintaining rigor and transparency in analysis.

5

Results of QCA and Thematic Analysis

Building upon the research methodology established in Chapter 4, this chapter presents the findings of the fsQCA and thematic analysis conducted to identify factors explaining varying policy performance in different states under Component B of the PM-KUSUM scheme. Section 5.1 begins by describing the raw data and detailing the calibration process used to transform it into calibrated datasets. This section also introduces the three types of solutions generated in the QCA analysis. Section 5.2 then explains the development of the thematic analysis, outlining the process of identifying themes and codes from the semi-structured interviews. In Section 5.3, the results of the QCA are presented for states with both positive and negative performance in Component B. Each solution pathway is explored in detail, starting with the conditions that are present or absent, followed by an in-depth interpretation of what each pathway signifies. Insights from the thematic analysis are then integrated to offer a holistic understanding of the factors driving positive or negative policy performance in the respective regions. Section 5.4 highlights supplementary insights from the thematic analysis that were not fully captured through the QCA solution pathways. Lastly, Section 5.5 addresses the robustness and sensitivity checks performed to validate the findings. This includes an analysis of how changes in consistency and calibration thresholds affect the positive and negative solution pathways.

5.1. Raw datasets, calibrated datasets and types of solutions of fsQCA

The raw data used to metricize the performance of the states in the policy is the installed solar pumps as a percentage of sanctioned solar pumps which is tested as the outcome for the component B of PM KUSUM scheme. The metric of installed pumps as a percentage of sanctioned pumps is chosen because it can to an extent capture the interest of the state government while also in part account for the differences of need for the state. The data for the outcomes observed in component B is obtained through PM KUSUM website as on 30th September 2024(MNRE, 2019). The state wise outcomes for the component of interest of PM KUSUM are shown in the table 5.1. The outcomes for all union territories except for Jammu & Kashmir were not counted in the analysis due to the lack of data on the sanctioned quantities. Similar to the union territories due to lack of outcome data for the states of Andhra Pradesh and Sikkim the states were excluded from the analysis. Due to the lack of reliable data for the factors affecting the sanctioned quantities for solar installations the union territory of Ladakh,it was excluded from the analysis.

For the factors tested, each component was tested with a limited number of factors as suggested by Pappas and Woodside, 2021 due to the increasing complexity if too many causal factors are tested. If too many causal conditions were included it would have lead to over-fitting of causal conditions. For this study the number is restricted to the square root of the sample size which was 25, hence the variables tested were restricted to 5. This is considered among the best practices for QCA analysis. For component B the factors tested were ideological alignment the regional and national level governments, the farmers monthly income, the GSDP per capita for the state, solar RPO compliance of the states prior to adoption and the annual irrigation draft normalized for net area sown. The explanations of choosing of the variables are summarized in table 4.3. The raw datasets for component B are shown in the tables in the appendix B.

States	Sanctioned	Installed	Installed vs sanctioned(%)
Arunachal Pradesh	700	380	54.29
Assam	4000	0	0.00
Chhattisgarh	10000	0	0.00
Goa	900	79	8.78
Gujarat	12382	7402	59.78
Himachal Pradesh	1270	638	50.24
Haryana	197655	133980	67.78
Jammu & Kashmir	5000	1567	31.34
Jharkhand	42985	17632	41.02
Karnataka	41360	1373	3.32
Kerala	100	8	8.00
Maharashtra	405000	138665	34.23
Meghalaya	3035	96	3.16
Manipur	150	78	52.00
Madhya Pradesh	59400	7325	12.33
Mizoram	1700	0	0.00
Nagaland	265	65	24.53
Orissa	6441	5120	79.49
Punjab	53000	12952	24.44
Rajasthan	262914	77884	29.62
Tamil Nadu	5200	3275	62.98
Telangana	0	0	0.00
Tripura	10895	3025	27.77
Uttarakhand	5685	318	5.59
Uttar Pradesh	110948	52981	47.75
West Bengal	0	0	0.00

Table 5.1: Raw Dataset for Installed pump-sets as a percentage of the sanctioned pump-sets(MNRE, 2019)

Once the raw datasets are collected and normalized to account for differences between states in India, the datasets were fitted into a log odds curve to form the calibrated datasets. These datasets represent the raw data in the range of 0 to 1 with 0 representing non-membership of the data point, 1 representing full membership of the data point, and 0.5 representing neither fully in nor fully out membership of the data point(Pappas and Woodside, 2021). This is shown in table 5.2. The calibrated datasets for component B are shown in appendix B.

Fuzzy-set value	**Membership**
1	Full membership
1 < data < 0.5	Fully-in
0.5	Not fully-in not fully-out
0.5 < data < 0	Fully-out
0	No-membership

Table 5.2: Fuzzy-set values and their membership(Singh, 2022)

The calibration thresholds chosen for each of the tables were as suggested by Pappas and Woodside, 2021 in their analysis. For normal distributions the calibration thresholds were chosen at 95th percentile, 50th percentile and 5th percentiles of the dataset to be calibrated for fully in, crossover and fully out respectively. For left or right skewed distribution the calibration thresholds were chosen at 80th percentile, 50th percentile and 20th percentiles of the dataset to be calibrated for fully in, crossover and fully out respectively. The calibration set points for each dataset are represented in the table 4.4.

Once the datasets were calibrated the truth tables were generated with the truth table showing all possible outcomes(positive or negative) which are available with the presence or absence of causal conditions. The truth table of component B is shown in the appendix B. The truth table then was boiled down into solutions of causal mixes which lead to the outcome observed. The consistency threshold is kept at 0.80 to make sure that the configurations reliably predict the outcome by requiring that 80% of cases with a given configuration exhibit the outcome. This balance enhances the robustness and interpretability of the results(Schneider and Wagemann, 2012). If there were no solutions apparent at the consistency threshold of 0.8 the consistency threshold was lowered to the minimum mandated value of 0.75 as suggested by Pappas and Woodside, 2021. The causal mixes/solution pathways/solution configurations are the configurations of conditions which are reflected in every solution outcome corresponding to the characteristics of the states that performed well or not.

In fsQCA, the terms complex, parsimonious, and intermediate solutions refer to varying levels of simplification when analyzing configurations that led to an outcome (Ragin, 2008a). The complex solution takes into account all possible causal combinations without relying on simplifying assumptions, thereby ensuring high coverage. In contrast, the parsimonious solution used only the necessary causal conditions, identified with the aid of logical remainders (simplifying assumptions for cases that do not exist in the data). This often results in overly simplified models that may overlook relevant causal pathways. The intermediate solution strikes a balance between these extremes, integrating theoretically plausible simplifying assumptions providing a more nuanced understanding of causality while preserving key conditions. This approach blends empirical evidence with theoretical insights to create a more practical and interpretable model (Pappas and Woodside, 2021).

Once the solution pathways are generated, initial observations are made regarding whether specific conditions are present or absent in leading to the observed outcomes. These QCA-generated solutions served as the foundation for developing questionnaires used in semi-structured interviews. Insights from these interviews were then analyzed through inductive thematic coding to identify emerging themes. The findings from this thematic analysis further enriched the understanding of the QCA solution pathways.

5.2. Thematic analysis development

The process of thematic coding starts with reading through the transcripts of the semi-structured discussions which were the basis of the analysis. These interviews were conducted with key individuals as mentioned in section 4.3.2. Once the researcher familiarized with the content that is being analyzed the development of codes took place. Some initial codes were developed on the basis of the transcript. Inductive thematic coding is an iterative process which has the advantage of refining and/or adding codes as new insights develop over analysis. Through the iterative nature there is good rigor developed and the analysis can be more nuanced capturing of complexities of interview data(Fereday and Muir-Cochrane, 2006). The codes developed over this process are shown in the table 5.3. The number of respondents who mentioned the topic discussed in the code was also identified. This was not indicative of the importance of the topic that is being discussed in the code. As Braun and Clarke, 2013 mention, thematic analysis prioritizes the quality of the data and richness of themes that emerge, rather than how often they are mentioned.

Code Group/Code	Frequency
Agriculture	
Access to electricity	8/9
Free/Subsidized electricity for farmers	4/9
Land Fragmentation	2/9
Diesel pumps to replace	3/9
Irrigation demand/ need	2/9
Economic	
Resource of the farmer	7/9
Access to credit	7/9
Resource of the state	6/9

Implementation Agency	
Agency choice	7/9
Agency Resources	8/9
Agency Will	4/9
The co-ordination of departments	6/9
Pilots and experimentation	6/9
Implementation Vendor	
Vendor participation	7/9
After sales service	8/9
Political	
Government mandate	8/9
Political alignment	6/9

Table 5.3: The codes identified from thematic analysis and the number of respondents who mentioned the topic around the code(Authors Analysis)

5.3. Results of fsQCA and thematic analysis

This section presents the results of the fsQCA and thematic analyses for Component B of the PM KUSUM scheme, structured into three parts. The first part examines positive outcomes under specific conditions, while the second part explores negative outcomes under another set of conditions. Finally a short note on some of the general observations is discussed in a section. The solutions are visually represented, with green indicating the presence of a condition contributing to the outcome, red indicating its absence, and white indicating that the presence or absence of the condition does not significantly impact the outcome. Each solution pathway is analyzed by first identifying which conditions are present or absent, followed by insights developed through the thematic analysis to further interpret the solution pathways.

In the context of Qualitative Comparative Analysis (QCA), a solution pathway refers to a combination of the presence or absence of conditions, or independent variables, that consistently lead to a specific outcome. In this analysis, the outcome was measured by the percentage of solar pumps installed relative to the number sanctioned. The solution pathways identify configurations of five independent variables—ideological alignment between regional and national governments, farmers' monthly income, GSDP per capita, solar RPO prior to scheme implementation, and annual groundwater irrigation draft—the presence or absence of which explain variations in outcomes across states.

The ideological alignment variable captures whether both regional and national governments belong to the same party or coalition for most of the scheme's implementation period, potentially influencing policy support. Solar RPO for the financial year 2018-19, which measures the percentage of electricity sourced from solar energy, indicates whether there was already a push for solar initiatives in the region. Farmers' monthly incomes reflect their financial capacity to bear the capital costs associated with adopting solar water pumps. Meanwhile, GSDP per capita serves as a proxy for the state's economic resources, reflecting its overall financial health. Lastly, the annual groundwater irrigation draft acts as an indicator of irrigation demand within the state.

By examining these solution pathways, the goal was to understand the diverse policy outcomes and determine which factors or combinations of factors have a decisive impact. Each configuration was assessed using consistency and raw coverage scores. Consistency measures how well the configurations align with the observed outcomes (Elliot, 2013), while raw coverage indicates the extent to which each configuration explains the outcome (Florea et al., 2019).

To further understand how the presence or absence of specific conditions affected solar pump installations, it was essential to explore these configurations in detail. Expert insights were gathered through semi-structured interviews to better comprehend the combined effects of the identified factors. The interview questions were informed by the QCA results, as well as insights drawn from academic and grey literature. The solution configurations and observations derived from the solution pathways are discussed, followed by insights from the thematic analysis for each pathway. The overall themes that emerged from these discussions are summarized in Table 5.3.

5.3.1. Results of the QCA for positive outcomes of component B of PM KUSUM

In the fsQCA analysis of outcomes in component B, with a consistency threshold set at 0.80, the resulting solution exclusively comprises positive outcomes. This indicated that the solution only encompasses configurations leading to positive outcomes, while omitting any causal configurations associated with negative outcomes. The reported raw coverage ranges from 0.1 to 0.2, with each solution exhibiting a high consistency score above 0.84. The solutions collectively achieve an overall consistency of 0.85 and a coverage of 0.39. Hence, a high consistency score, such as 0.85, corresponded with a moderate coverage value, like 0.39 in this analysis. The states which show a positive outcomes under component B are Maharashtra, Rajasthan, Uttar Pradesh, and Haryana.

Figure 5.1: Results of fsQCA for positive outcomes component B

Solution 1(Rajasthan): ALI*FMI*GSDP*RPO*AID

The first solution pathway had a consistency score of 0.92 and raw coverage of 0.055, reflecting the state of Rajasthan exhibiting positive outcome. As noted earlier, the solution pathway indicates a combination of presence or absence of a conditional variable. The ideological alignment of regional and national governments refers to whether they belong to the same party or coalition for the majority of the scheme's implementation period. Solar RPO compliance for the financial year 2018-19, which measures the percentage of electricity sourced from solar energy, indicates whether there was an existing push for solar initiatives in the region. The variable of farmers' monthly incomes reflects their capacity to cover the capital costs of solar water pumps. The GSDP per capita reflects how the state is doing financially and serves as a proxy for the state's economic resources, while the annual groundwater irrigation draft indicates overall irrigation demand. In this configuration, farmers' incomes and solar RPO compliance were present, while GSDP per capita, ideological alignment, and annual groundwater irrigation draft were absent.

This solution pathway suggests that non-alignment between regional and national governments does not hinder positive performance in implementing PM KUSUM Component B. The analysis shows that, despite a lower GSDP per capita indicating less prosperous financial conditions, relatively higher farmer incomes compared to other regions support adoption. Additionally, the early adoption of solar technologies suggests a pre-existing push for solar energy even before the scheme's roll out. The irrigation demand in this solution configuration is observed to be lower compared to other regions.

Insights from thematic analysis indicated that ideological differences between regional and national governments do not necessarily impede the adoption of solar water pumps under Component B. Participants emphasized that strong regional-level commitment, regardless of political alignment, along with demand and available resources, can drive successful policy outcomes. This strong commitment is also reflected in the fact that the region had a successful pilot for solar water pumps installation carried out by the horticultural department in the state of Rajasthan (Goyal, 2013). Early pilots and experimentation with solar water pumps prior to the scheme's implementation was mentioned to be a factor to contribute to institutional knowledge and capacity, facilitating smoother adoption under PM KUSUM.

The lower irrigation requirements can be attributed to factors such as an arid climate or the cultivation of less water-intensive crops, which reduce the overall need for groundwater irrigation. However, despite these lower requirements, there remains significant demand for solar water pumps which was noted to be due to unreliable electricity access, often leading farmers to rely on diesel pumps. Rising diesel prices further seemingly incentivized this shift, eliminating recurring fuel costs and aligning with sustainable agricultural practices (Khanna, 2024).

A key factor influencing the adoption of solar water pumps is farmer income, shaped by elements such as crop types, diversification, and landholding size (Das and Ganesh-Kumar, 2018). A farmer's income is critical in determining their ability to cover up to 40% of the upfront costs for solar pumps, as highlighted in prior studies and supported by thematic analysis(Powell et al., 2021; Rathore et al., 2018). In this solution configuration, higher farmer incomes enable the demand for solar pumps to translate into actual installations, despite the lower overall GSDP per capita and the non-alignment of regional and national governments.

Solution 2(Uttar Pradesh): ALI*FMI*GSDP*RPO*AID

This solution configuration revealed a solution consistency of 0.92 and raw coverage of 0.15, indicating positive performance in the case of Uttar Pradesh under Component B of PM KUSUM under certain conditions. Specifically, these conditions include the presence of ideological alignment, higher solar RPO percentages, and higher annual groundwater irrigation needs, while farmers' incomes and GSDP per capita were notably absent. The alignment between state and central governments during the scheme's roll out appeared to have played a critical role in driving its success. Additionally, higher solar RPO signaled a regional interest in solar energy adoption prior to scheme being announced. The relatively high demand for groundwater irrigation further seems to boost the need for solar water pumps. Interestingly, despite the absence of high farmers' incomes, which would typically signal the ability to cover capital costs, and lower GSDP per capita reflecting limited state resources, positive adoption had still been observed.

The thematic analysis highlighted that one of the main drivers behind solar pump adoption was irrigation demand, particularly prominent in states like Uttar Pradesh. Access to electricity, or the lack thereof, was often sighted as a possible factor as this could significantly influences farmers' willingness to participate in the scheme.Participants also reflected that in states where obtaining new electricity connections is slow, or where land fragmentation poses challenges, often saw interest in adopting solar pumps (Khanna, 2023). Land fragmentation could possibly complicate access to agricultural electricity, as land divided among family members may not be properly reflected in state records, thus excluding farmers from eligibility to avail electricity connections(AgriFarming, 2024).

The thematic analysis also revealed that with the reliance on diesel pumps for irrigation, rising fuel prices served as a strong incentive for both the government and farmers to shift towards solar alternatives. This shift not only eliminates fuel expenses but also promotes sustainable agricultural practices. Increasing diesel costs push farmers to explore more cost-effective solutions(Khanna, 2024).

Political alignment between state and central governments emerged as a possible factor in shaping policy priorities in certain cases as revealed in thematic analysis. According to some participants, a few states with ideological ties to the central government were more likely to align closely with national initiatives, which can streamline implementation processes and enhance the effectiveness of policies (Niedzwiecki, 2018). This alignment also could have possibly influenced the allocation of critical state financial resources essential for the scheme's success. The state's existing emphasis on solar energy, reflected in its infrastructure even before the scheme's introduction, seemingly further contributed to its positive performance which was re-emphasized as a factor to affect policy performance by experts.

Despite limited economic resources, both among farmers and the state, political will had proven to be a decisive factor. The commitment to supporting the scheme possibly enabled the efficient allocation of limited state resources, thereby contributing to its successful implementation. Participants noted that this political willingness has been crucial in maximizing the impact of constrained resources, ultimately leading to favorable outcomes.

Solution 3(Maharashtra): ALI*FMI*GSDP*RPO*AID

This solution pathway highlighted the positive performance observed in Maharashtra, characterized by a consistency score of 0.83 and a raw coverage of 0.21. In this scenario, ideological alignment and farmers' incomes were not prominent factors, while the presence of a higher GSDP per capita, higher solar RPO prior to the scheme's implementation, and significant annual groundwater irrigation were seemingly present. The high groundwater irrigation draft in the region indicated a possible demand in the region for water pumps. Notably, the absence of political alignment with the national government did not hinder positive performance. The state's prior commitment to solar energy, as seen in its energy mix before the scheme's announcement, was a possible driver. Despite the relatively low incomes of farmers, successful adoption was achieved, even though farmers were constrained by the inability to cover higher capital costs. The GSDP per capita of the region being high indicates ability of the state to put up their portion of subsidy component.

Interviewees revealed that ideological differences between regional and national governments do not necessarily obstruct the adoption of solar water pumps under Component B. Participants emphasized that strong regional commitment, regardless of political alignment, coupled with demand and available resources, can drive successful policy outcomes. Maharashtra's prior investments in solar energy, as evidenced by higher solar RPOs, demonstrated its proactive stance. The state had garnered significant interest in solar energy, especially since it pioneered feeder-level solarization, making it a testing ground for solar water pumps (Gambhir et al., 2021). This early adoption showcased the state's dedication to integrating solar solutions into agriculture (Gambhir et al., 2021).

Maharashtra's positive performance appeared to be driven by a strong regional mandate to implement Component B of the PM-KUSUM scheme. The state's higher GSDP per capita reflected its relatively strong financial health (Hindustan Times, 2024; Mukherjee, 2022), enabling substantial subsidies—covering 60% of solar pump capital costs from the state government themselves, reducing the burden on farmers to just 10%. This financial support was pivotal in facilitating adoption, especially given the limited financial capacity of farmers in this case. Economic resources at the state level play a crucial role in the success of policies like solar water pump programs (Rubin and Zorn, 1985). The generous subsidy structure effectively lowered entry barriers for farmers, allowing broader participation.

Further it was noted by a few participants that, higher irrigation needs in the region, compounded by challenges like fragmented land ownership and extended wait times for electricity connections, had also driven demand for solar water pumps (AgriFarming, 2024; Khanna, 2024). In cases where access to electricity remained inadequate, farmers often resorted to using diesel pumps. The recurring costs associated with diesel pumps, coupled with increasing diesel prices, further incentivized the switch to solar pumps (Khanna, 2024).

Overall, the successful adoption in Maharashtra appeared to result from a combination of demand for solar water pumps, the state's economic resources, and a proactive approach to addressing this demand, bolstered by a history of solar energy adoption.

Solution 4(Haryana): ALI*FMI*GSDP*RPO*AID

This solution pathway highlighted the positive outcome observed in Haryana, characterized by a consistency score of 0.87 and a raw coverage of 0.15. The state's success was observed to be driven by a combination of high annual groundwater irrigation requirements, ideological alignment between regional and national governments, relatively high farmer incomes, and a strong GSDP per capita, despite a lower prior solar RPO percentage. The high irrigation demand underscored a clear need for pumps, and the ideological alignment with the central government may have further facilitated adoption by aligning policy priorities. The state's high GSDP per capita indicated greater financial resources, while the relatively high farmer incomes suggested that many farmers were financially capable of covering capital costs. Notably, the absence of prior solar energy adoption did not impede the uptake of solar water pumps.

Thematic analysis revealed that significant irrigation demand, coupled with the need for solar water pumps, had been a crucial factor in driving the scheme's success. This demand can be attributed to unreliable electricity access, often resulting from lengthy wait times for connections or land fragmentation(Khanna, 2024). Such challenges push farmers to rely on diesel pumps, which incur recurring fuel costs that are further inflated by rising diesel prices. The alignment of state policies with those of the national government had streamlined the adoption process. Interviews indicated that when state governments share ideological alignment with the central government, they were more likely to prioritize national initiatives, thereby improving policy implementation (Niedzwiecki, 2018). This alignment enhanced the state's capacity to address agricultural needs while reinforcing its commitment to renewable energy, contributing to the effective implementation of PM-KUSUM Component B. Notably, despite Haryana's lack of previous solar initiatives, adoption rates remained strong.

Another key factor driving adoption, as revealed through thematic analysis, was farmers' income levels and access to resources, which are influenced by factors such as crop type, diversification, and landholdings (Das and Ganesh-Kumar, 2018). A farmer's financial capability was critical in deciding whether the farmer could cover the upfront costs for solar water pumps, as prior research also indicates(Rathore et al., 2018). Additionally, the thematic analysis underscored that a state's economic resources significantly impact the success of such policies(Rubin and Zorn, 1985). States with limited financial resources often struggle to implement these policies effectively, as they may lack sufficient support mechanisms for farmers. In contrast, economically robust states like Haryana have exceeded the required subsidy levels(Khanna, 2024). Specifically, Haryana offered subsidies covering 45% of the initial capital cost for solar water pumps, surpassing the mandated 30%, due to its stronger economic foundation. This financial strength enabled the state to alleviate the upfront cost burden on farmers effectively, reducing their barrier to entry.

Haryana's successful adoption of solar water pumps could be attributed to a combination of strong demand, ideological alignment between state and national governments, and substantial financial resources at both the state and farmer levels. These elements collectively contributed to the state's strong performance in implementing PM-KUSUM Component B.

In examining the common characteristics of successful adoption of solar water pumps under Component B of the PM KUSUM scheme, a few factors stood out across multiple solution pathways. Interest in solar energy prior to the scheme's implementation was evident in three out of the four pathways. Similarly, high annual irrigation requirements appeared in three of the four pathways. Additionally, either state resources or farmers' resources are relatively higher compared to their peers in three of the four pathways. Two of the four solution pathways also highlighted higher GSDP per capita, suggesting strong state-level economic performance and relatively better financial standing. Similarly, two pathways indicated higher farmer incomes. Ideological alignment between the state and national governments was noted in two of the four pathways. Furthermore, two of the states with positive solution pathways, Rajasthan and Maharashtra, had pilot schemes in place prior to the launch of PM KUSUM(Gambhir et al., 2021; Goyal, 2013). Notably, each solution pathway aligned with the characteristics of a single state.

5.3.2. Results of the QCA for negative outcomes of component B of PM KUSUM

In the fsQCA analysis of negative outcomes in component B, with a consistency threshold set at 0.75, the resulting solution exclusively comprises negative performing states. The consistency score was lowered to the theoretical minimum of 0.75 for interpretable solutions, as at the consistency threshold of 0.8 there were no solution pathways(Pappas and Woodside, 2021). The reported raw coverage ranged from 0.17 to 0.22, with each solution exhibiting a moderate consistency score above 0.78. The solutions collectively achieved an overall consistency of 0.79 and a coverage of 0.45. Hence, a moderate consistency score, such as 0.78, corresponded with a moderate coverage value, like 0.45 in this analysis. The states which show a negative outcomes under component B were Meghalaya, Nagaland, Assam, West Bengal and Madhya Pradesh.

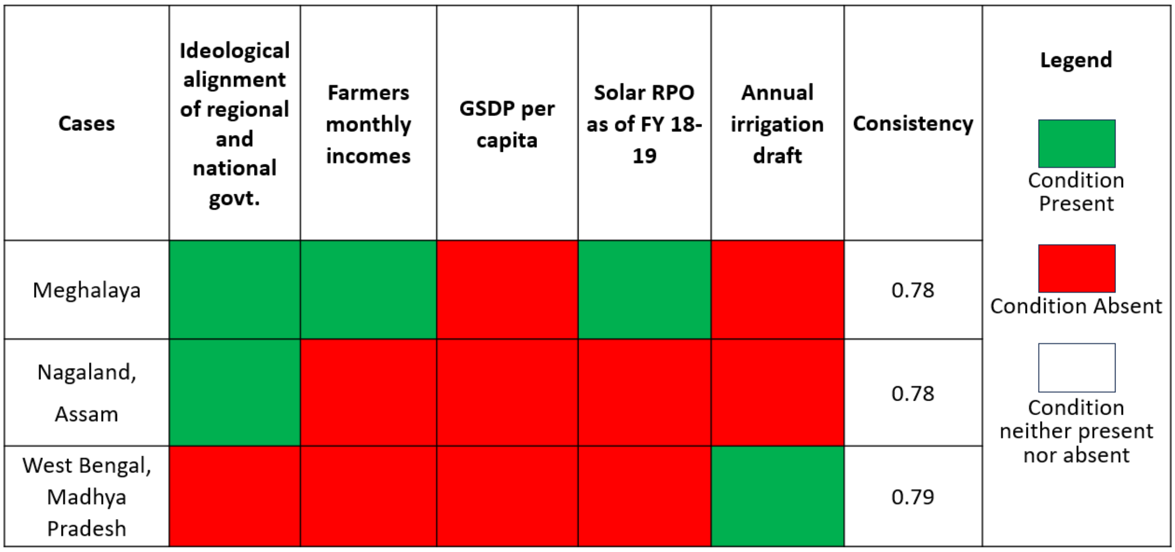

Figure 5.2: Results of fsQCA for negative outcomes of component B

Solution 1(Meghalaya): ALI*FMI*GSDP*RPO*AID

This solution pathway had a consistency score of 0.78 and a raw coverage of 0.18, indicating relatively lower solar water pump installations in Meghalaya. Here, factors such as ideological alignment with the national government, higher farmer incomes, and solar RPO were present, while both the annual irrigation draft and GSDP per capita were absent. The lack of irrigation demand suggested a reduced need for solar water pumps in the region. Additionally, the lower GSDP per capita highlighted the state's limited financial capacity to provide necessary subsidy support. Despite political alignment indicating policy support, strong solar RPO compliance signaling interest in solar initiatives, and higher farmer incomes suggesting the capacity to bear capital costs, adoption rates remained low.

Interestingly, despite these seemingly favorable conditions, Meghalaya showed limited uptake of solar water pumps under the PM-KUSUM scheme. This was especially surprising given the ideological alignment with the national government and the increase in central financial assistance to 50% (MNRE, 2019). A potential explanation lied in the state's constrained economic resources, as reflected in its lower GSDP per capita. Participants noted that limited financial capacity can hinder the state's ability to contribute to necessary subsidies, even with national support. Additionally, competing policy priorities could stretch the state's limited resources—both financial and human—reducing the implementing agency's capacity to effectively deploy the scheme.

Furthermore, specifically Meghalaya's humid climate and reduced irrigation needs contribute to lower demand for solar water pumps compared to other states (Ghosh, 2019). The lack of urgency for groundwater-based irrigation seemingly lessens the incentive to invest in solar pumps, even when supportive policies exist. Experts emphasized that reduced irrigation demand and subsequently lower demand for solar water pumps in some regions may lead to lower vendor participation. Interview insights suggested that the smaller scale of the state's orders could deter potential bidders, as vendors typically prefer larger, more profitable contracts. Consequently, the combination of limited state economic resources and low irrigation demand helped clarify why solar water pump adoption in Meghalaya remained slow, despite otherwise favorable conditions.

Solution 2(Nagaland and Assam): ALI*FMI*GSDP*RPO*AID

This solution pathway, with a consistency score of 0.78 and raw coverage of 0.22, highlighted the under performance of Component B of PM KUSUM in Assam and Nagaland. In this scenario, the ideological alignment between the state and national governments was present, while the conditions of farmer incomes, GSDP per capita, solar RPO, and annual groundwater irrigation draft were absent. The limited demand for irrigation in these regions indicated a reduced need for water pumps in general. Additionally, the financial constraints faced by both farmers and the state, as reflected in lower farmer incomes and GSDP per capita, were likely contributing factors to the low adoption rates. The historically low solar RPO compliance in these states also indicated a lack of prior momentum for solar initiatives, despite the ideological alignment that could potentially drive supportive policy objectives.

Assam and Nagaland, specifically, exhibit a clear lack of interest in adopting solar water pumps under PM KUSUM Component B, even with central financial assistance covering 50% of the costs (MNRE, 2019). These states faced significant economic hurdles, with low GSDP per capita reflecting limited financial capacity to support the scheme. Economic resources are crucial to the successful adoption of solar water pump programs (Rubin and Zorn, 1985). Interviewees noted that states with restricted financial resources often struggle to implement such policies effectively due to challenges in providing adequate support to farmers. The thematic analysis further revealed that states with limited budgets may prioritize other pressing needs over subsidy allocations for solar initiatives. Moreover, the thematic analysis indicated that the low income levels of farmers and minimal demand for groundwater irrigation diminish the perceived necessity for solar pumps, which is consistent with previous studies (Powell et al., 2021; Rathore et al., 2018). Participants in the semi-structured interviews also suggested that the lack of demand for solar water pumps was tied to the overall low irrigation requirements in these regions. The limited scale of orders placed by the states with lower demand, as highlighted in the interviews, may deter vendors who usually prioritize more lucrative, larger contracts.

Despite the ideological alignment between state and national governments in Assam and Nagaland, this political factor alone had not been sufficient to overcome the economic barriers and lack of interest in solar water pump adoption. This situation is similar to that observed in Meghalaya, where even with relatively higher farmer incomes, the state's limited financial resources and low irrigation demand hinder meaningful uptake of the scheme. Across these northeastern states, it is evident that both economic strength and agricultural demand were critical factors in driving solar water pump adoption, regardless of political alignment.

Solution 3(West Bengal and Madhya Pradesh): ALI*FMI*GSDP*RPO*AID

This solution pathway highlighted poorer performance in the states of West Bengal and Madhya Pradesh, with a consistency score of 0.79 and a raw coverage of 0.20. In this pathway, high irrigation draft was present, while farmer incomes, GSDP per capita, ideological alignment, and solar RPO compliance were absent. The findings suggested that limited financial resources, both at the farmer and state levels—as indicated by low farmer incomes and GSDP per capita—were likely constraining adoption. The lack of ideological alignment between regional and national governments may point to divergent policy objectives, while low solar RPO purchases prior to the scheme indicate minimal prior interest in solar energy initiatives. Despite the apparent demand for irrigation technologies, as suggested by high irrigation needs, adoption of solar water pumps remained low.

Several factors contributed to the limited uptake of solar water pumps under PM KUSUM Component B in these states. Economic constraints restrict the financial capacity of both farmers and state governments, as reflected in low farmer incomes and GSDP per capita. Interview participants noted that farmers with limited resources may struggle to cover the upfront costs required for solar water pumps.

Thematic analysis further suggested that states with constrained financial resources face challenges in providing sufficient support for such policies, leading to difficulties in effective implementation. This economic barrier, combined with a lack of prior interest in solar adoption, has likely impeded progress despite existing irrigation needs.

Another critical factor appears to be the lack of political alignment between state and central governments. Thematic analysis indicated that states not aligned with the central government often prioritize regional initiatives over national schemes, leading to delays and reduced emphasis on the latter. Interviewees emphasized that this misalignment can slow down the implementation process as well as lack of financial and human resource deployed for implementation of such a scheme, ultimately affecting the scheme's effectiveness.

In summary, despite the technical potential and substantial irrigation needs in West Bengal and Madhya Pradesh, a combination of weak financial resources, insufficient focus on solar initiatives, and political divergence collectively hinders the adoption of solar water pumps in these states.

In reviewing the characteristics of negative outcomes, all solution pathways pointed to lower GSDP per capita, indicating weaker state finances and relatively poorer states. A lack of interest in solar energy prior to the implementation of PM KUSUM is evident in two of the three pathways. Similarly, farmers' incomes appear to be lower compared to other states in two of the three pathways. Interestingly, there was ideological alignment between the national and state governments in two of the three pathways. Additionally, irrigation demand seems to be insufficient in two of the three configurations. One solution pathway corresponds to a single state, while the other two pathways each align with two states.

5.3.3. General observations from the results

In this study, only 9 out of 25 states were reliably categorized as having either positive or negative performance outcomes. The QCA highlighted specific cases that merit closer examination. For example, in Rajasthan, despite minimal apparent irrigation demand, thematic analysis revealed that farmers' eagerness to reduce diesel dependency—amplified by unreliable electricity access—created demand for solar water pumps. This demand, combined with farmers' financial capacity and the state government's active promotion of solar energy, contributed to the state's positive performance. Similarly, in Maharashtra, the irrigation demand was supported by the state's strong financial position and its general commitment to adopting solar energy.

In contrast, Uttar Pradesh presented an interesting case where financial constraints at both the state and farmer levels did not impede positive performance. Thematic analysis suggests that alignment between regional and national governments facilitated coordinated efforts for solar adoption. This, along with substantial irrigation demand and heavy reliance on diesel pump sets, likely drove the positive outcomes observed in the state.

On the other hand, the negative outcomes observed in the study revealed distinct patterns. Two solution configurations, encompassing Meghalaya, Nagaland, and Assam, pointed to a lack of irrigation demand as the primary barrier to adoption. In contrast, a separate configuration involving West Bengal and Madhya Pradesh displayed negative outcomes despite apparent irrigation demand. This could be attributed to a misalignment of state and national objectives, leading these states to prioritize their limited financial resources elsewhere. Additionally, insufficient financial capacity among farmers further dampened demand for solar adoption, even in the presence of irrigation needs.

5.4. Additional insights gained from thematic analysis

Despite the valuable insights gained through the QCA solutions—specifically on how factors such as political alignment, economic resources of both the state and farmers, and irrigation demand influence the scheme's performance—additional themes emerged from the semi-structured interviews and subsequent thematic analysis. These themes appear to possibly impact the positive or negative performance of the policy in certain regions but could not be effectively captured within the QCA framework due to a lack of reliable datasets to quantify their effects as variables. Key among these emerging factors were farmers' access to credit to cover their share of the subsidy, the implementation process, and vendor participation.

Access to Credit

Access to credit was consistently highlighted by participants as a significant barrier within the scheme, emerging as a prominent theme in the analysis. Although the scheme provides for 30% of the upfront cost to be covered by a loan, many farmers remain reluctant to take on such loans, often due to the complexities of the application process or difficulties in accessing credit. The lack of co-ordination between financial institutions like banks and the ministries responsible for implementing the scheme is a major contributing factor (PRSIndia, 2020).

Furthermore, bureaucratic hurdles often push farmers to rely on informal sources of financing instead (Narayanan, 2016). Financial institutions, for their part, were often noted to be hesitant to extend credit due to concerns about farmers' credit reliability, particularly regarding repayment histories and past defaults (Arora and Shukla, 2020; MicroSave, 2019). In many instances, it was revealed that farmers prioritize other urgent financial needs—such as loans for seeds, fertilizers, and other inputs—over investments in solar water pumps (Miller, 2017). This highlighted the complexity of credit access, suggesting that it warrants deeper examination.

Implementing Agency

Thematic analysis indicated that the effectiveness of policy implementation can vary significantly depending on the choice of the implementing agency. States often delegate this responsibility to departments like energy development, agriculture, or horticulture, each bringing its own strengths and challenges. Selecting the appropriate implementing agency involves careful consideration of multiple factors, such as the department's commitment to advancing the policy and its proactive approach (Khanna, 2024; Niedzwiecki, 2018).

Moreover, the resources available to these agencies, both financial and human, were crucial for effective policy execution. These resources can be influenced by the state's economic conditions and the political support the agency receives. Coordination between departments was also vital for successful implementation, as highlighted in the interviews (Agir et al., 2023). For example, if the agricultural department was leading implementation, close collaboration with the energy development agency is essential to leverage technical expertise on solar pumps. Conversely, energy-focused agencies can benefit from the agricultural department's local presence for better outreach. Pilot projects conducted before full-scale launches were also noted as beneficial for refining processes, building networks, and learning from initial challenges (Pasupalati et al., 2022).

A streamlined system for handling complaints is another critical factor that shapes farmers' willingness to adopt solar pumps, as highlighted by interviewees. Ensuring that the process for lodging complaints is straightforward and accessible helps build trust, thereby increasing adoption rates.

Vendor Participation

Insights from thematic analysis emphasized the vital role of vendor availability and responsiveness in fostering trust among farmers. Highlighted by experts, in remote areas, logistical challenges and high costs often make it financially unfeasible for vendors to provide adequate support. This can erode farmers' trust, as they may hesitate to adopt solar pump technology if they cannot rely on timely maintenance and service. Additionally, resource constraints—both financial and human—further complicate the installation process, particularly in remote regions where deploying skilled personnel is challenging.

Moreover, as discussed earlier in the cases of Meghalaya, Assam, and Nagaland, interviewees noted that the scale of the state's orders significantly influenced vendor participation. Smaller contracts are less attractive to vendors who prefer larger, more profitable projects, reducing the pool of potential bidders. Another critical issue raised by vendors was delayed payments from the implementing agency. Timely payments are essential for maintaining cash flow, and vendors stressed that assurances of prompt payment would increase their willingness to participate in the bidding process, thereby enhancing project implementation and scalability.

5.5. Sensitivity and robustness analysis

This section examines the sensitivity of QCA results to changes in key parameters. Sensitivity and robustness checks are interrelated tools crucial for assessing the reliability and validity of findings (Oana and Schneider, 2024). While sensitivity analysis evaluates how changes in assumptions, parameters, or inputs influence outcomes, robustness checks ensure consistency across varied methodological decisions, together enhancing the stability and credibility of the results. As emphasized by Oana and Schneider, 2024, testing calibration, consistency, and frequency thresholds is essential to ensure robust conclusions. The analysis begins by observing variations in results when the consistency threshold is altered. Then, the thresholds for both dependent and independent variables were tested for sensitivity by adjusting them by ±5% to evaluate the robustness of the results.

5.5.1. Lowering or increasing consistency threshold

When the consistency threshold for the solution pathways, as shown in Figure 5.3, is increased, the number of solution pathways decreased to three, with the solution pathway for Maharashtra being omitted from the analysis. This suggests that at a higher consistency level, fewer pathways lead to positive outcomes, but the reliability of these remaining solutions becomes stronger. Increasing the consistency threshold in fsQCA reduces the number of solution pathways, making the remaining solutions more reliable but potentially lowering the coverage of cases explained(Huarng, 2015).

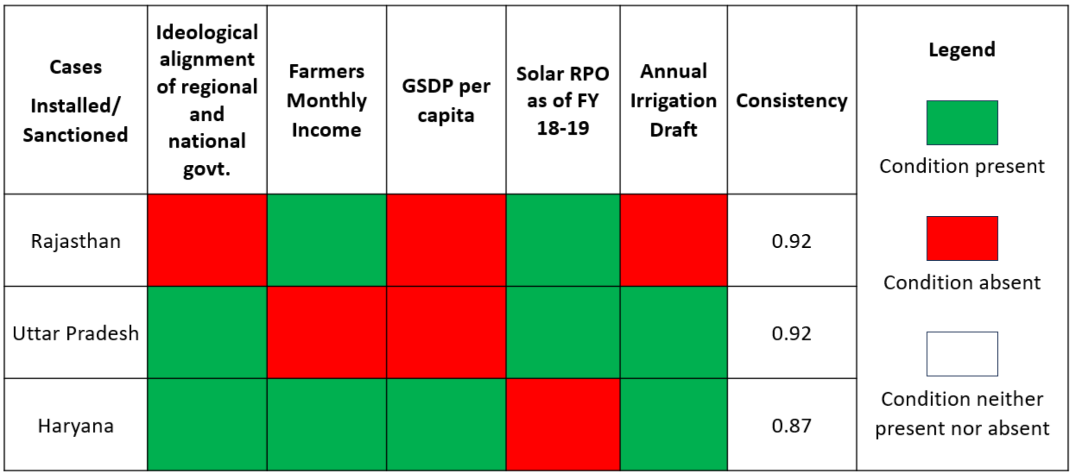

Figure 5.3: Results of fsQCA for positive outcomes component B with a consistency threshold set at 0.85

Conversely, when the consistency threshold for positive outcomes is lowered to 0.75, more cases were included, reducing the overall reliability of the solution. At this threshold, which is the minimum recommended by Pappas and Woodside, 2021, the states of Chhattisgarh, Orissa, Punjab, Tamil Nadu, Jharkhand, and the union territory of Jammu & Kashmir show positive outcomes, as illustrated in the figure 5.4. Lowering the consistency threshold in fsQCA increased the number of solution pathways but may introduce more uncertain or less reliable patterns in the results(Ragin, 2008b).

Here the case of Chhattisgarh was especially anomalous, displayed by the solution to have a positive outcome even though the state has not installed a single solar water pump under PM KUSUM Component B. Instead, there is a state scheme which had been very successful, with the highest number of solar water pump-sets installed under their state scheme of Saur Sujala Yojna[SSY](Khanna, 2024). It was to be noted that while Chhattisgarh has not yet participated in Component B, the state may plan to do so in the 2024–25 cycle of the scheme, as per Khanna, 2024.

Orissa had the highest number of installations as a percentage of sanctioned pumps (MNRE, 2019). Similar to Uttar Pradesh, aside from the lack of alignment with the national government, the state had a prior interest in adopting solar energy before the policy's implementation. Additionally, irrigation demand in the region drives higher adoption rates. This had occurred despite the absence of political alignment between the state and national governments, and despite limited resources available to both farmers and the state itself.

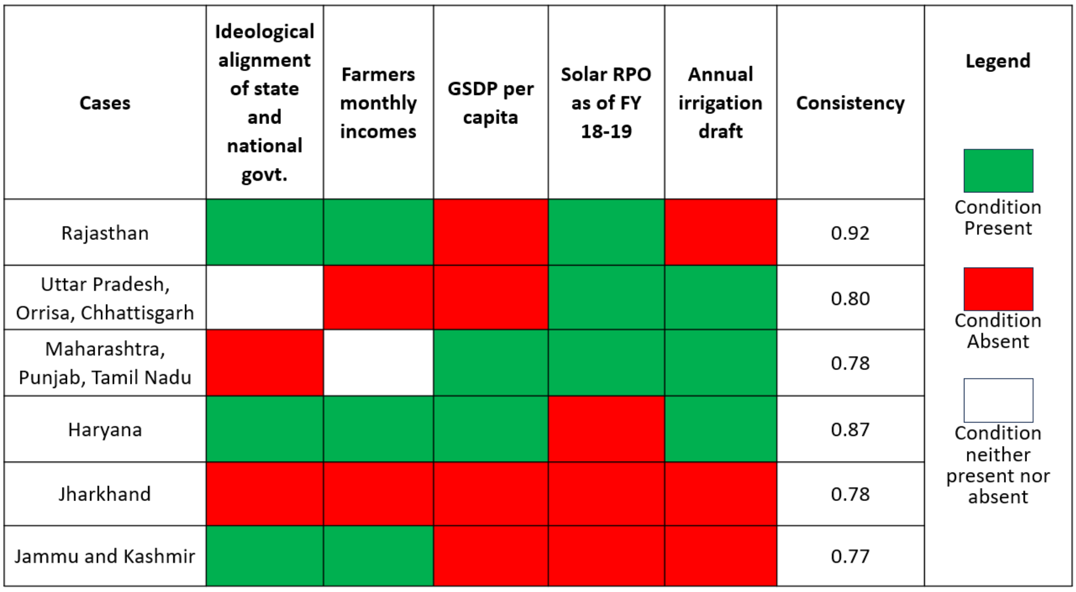

Figure 5.4: Results of fsQCA for positive outcomes component B with a consistency threshold set at 0.75

Punjab and Tamil Nadu exhibited a similar solution configuration to Maharashtra, with the key difference being higher farmer incomes in these two states. The moderately better performance, as compared to other states, in Punjab and Tamil Nadu can be attributed to their irrigation needs, prior interest in solar energy adoption before the implementation of the PM KUSUM scheme, and comparatively higher state resources. This is despite the lack of ideological alignment between the state and national governments.

The moderate success of Jharkhand under PM KUSUM cannot be fully explained by typical explanatory variables, as the state is relatively poor, has low farmer incomes, no political alignment with the national government, no prior push for solar energy, and low irrigation demand. However, the state's performance can be attributed to the integration of the JOHAR scheme into Component B of PM KUSUM. Jharkhand had already been installing solar water pumps under the JOHAR scheme, and remote farmers in the region, lacking access to electricity, demonstrated a strong demand for solar water pumps (Durga and Gaurav, 2024; Tiwary et al., 2021).

The relatively positive performance of Jammu & Kashmir under PM KUSUM can be attributed to ideological alignment, as the region has been under governor's rule since the scheme's implementation. Additionally, higher farmer incomes in the region suggest a greater willingness to adopt solar pumps, further supported by increased central financial assistance from the national government. This occurs despite lower state resources, no prior interest in solar energy, and lower irrigation demands.

When the consistency threshold in fsQCA is lowered, more solution pathways emerge, but with greater uncertainty. For instance, Chhattisgarh is marked as having a positive outcome, despite no solar pump installations under PM KUSUM, reflecting an inconsistency. Similarly, Jharkhand shows moderate success, despite the absence of strong explanatory factors chosen. These examples highlight how reduced thresholds can introduce ambiguous or unexpected results.

When the consistency threshold is increased to 0.8, no solution pathways are exhibited for the negative outcomes. Lowering the threshold further is not recommended, as a consistency level of 0.75 is considered the minimum for observing meaningful outcomes, as suggested by Pappas and Woodside, 2021. Maintaining a higher threshold helps preserve the reliability of the analysis while avoiding less certain or weaker results.

5.5.2. Changing calibration thresholds

The changes to the calibration threshold with a 5% increase yield the solutions shown in Figure 5.5 for positive performance and Figure 5.6 for negative performance of Component B of PM KUSUM. The consistency thresholds for both solutions were maintained at 0.80.

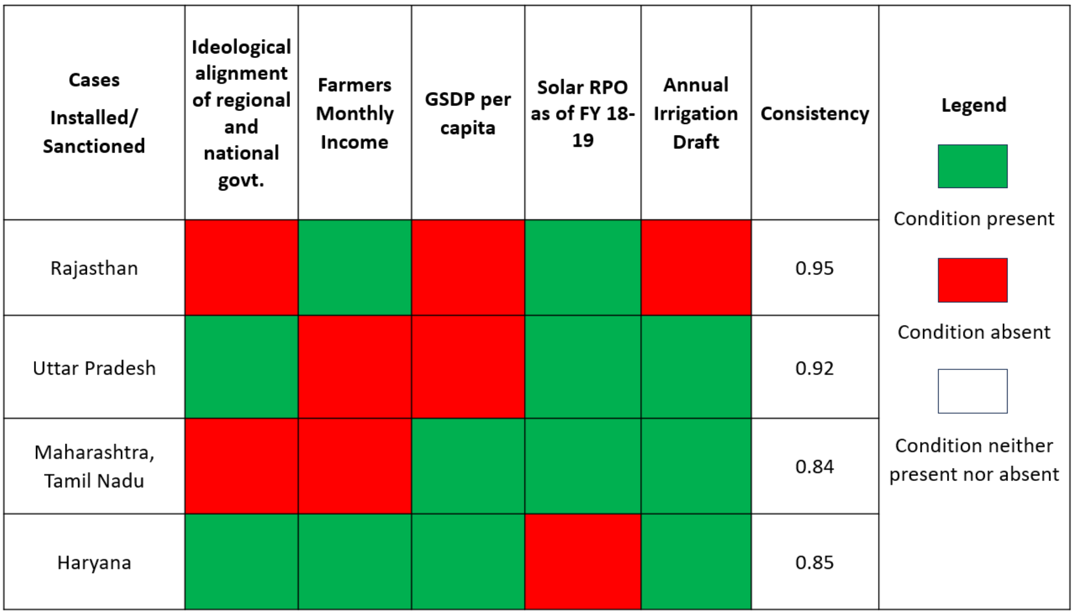

Figure 5.5: Observed solution pathways for positive performance with a 5% increase in calibration thresholds

With a 5% increase in the calibration thresholds, the number of solution pathways for positive performance remains unchanged from those generated with the original thresholds. The overall solution consistency is 0.86, with a raw coverage of 0.44. Four of the five states identified as positive adopters under Component B of PM KUSUM remain the same, while Tamil Nadu is introduced alongside Haryana, Maharashtra, Rajasthan, and Uttar Pradesh.

Tamil Nadu followed a solution pathway similar to that of Maharashtra, suggesting that the positive performance of the policy in Tamil Nadu was seemingly driven by similar explanatory factors. Despite a lack of ideological alignment and relatively lower farmer incomes, positive policy outcomes were associated with prior adoption of solar energy, stronger state economic resources, and regional irrigation requirements. Although Tamil Nadu's total installed solar pumps are lower, its installations as a percentage of sanctioned pumps remain high.

For negative performance, a 5% increase in the calibration thresholds does not change the number of solution pathways; however, the pathway identifying Nagaland and Assam as negative performers was replaced by a new pathway. The overall solution consistency remained 0.80, with raw coverage at 0.44. Three of the five states identified as negative adopters under the original thresholds persist, with Punjab and Karnataka introduced alongside Meghalaya, West Bengal, and Madhya Pradesh.

Punjab and Karnataka displayed negative outcomes in the newly introduced pathway. Although these states share some common challenges, their performance differs: Punjab shows moderate progress relative to sanctioned targets, while Karnataka's performance is lower. Both states face implementation challenges tied to a lack of ideological alignment, leading to inconsistencies in policy execution.

The changes to the calibration thresholds with a 5% decreased produce the solutions depicted in Figure 5.7 for positive performance and Figure 5.8 for negative performance of Component B of PM KUSUM. The consistency thresholds for both solutions were maintained at 0.80.

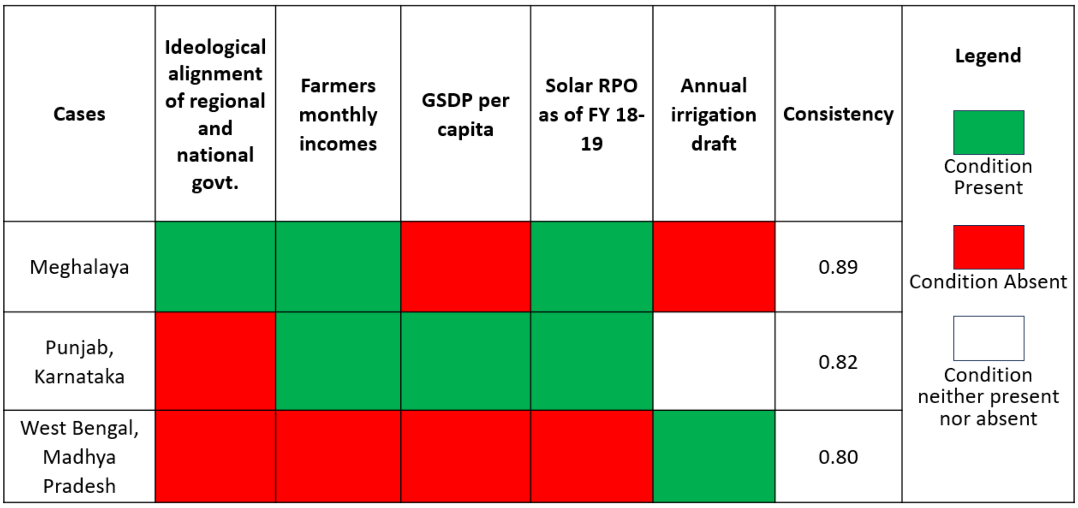

Figure 5.6: Observed solution pathways for negative performance with a 5% increase in calibration thresholds

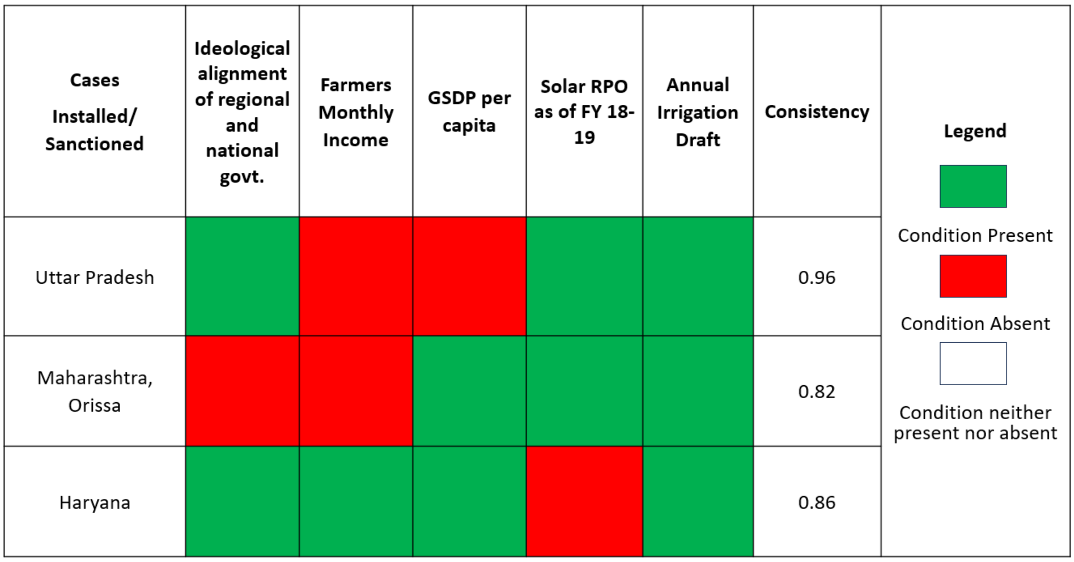

Figure 5.7: Observed solution pathways for positive performance with a 5% decrease in calibration thresholds

With a 5% decrease in the calibration threshold, the number of solution pathways for positive performance decreased from four to three. The overall solution consistency remains 0.86, with a raw coverage of 0.49. Three of the four states identified as positive adopters under the original thresholds remain, while Orissa replaces Rajasthan alongside Haryana, Maharashtra, and Uttar Pradesh.

Orissa exhibited a pathway to positive policy performance similar to Maharashtra. Despite a lack of ideological alignment and lower farmer incomes, positive outcomes are driven by factors such as prior adoption of solar energy and regional irrigation requirements (MNRE, 2019). Although Orissa has fewer installed pumps in absolute terms, its installations as a percentage of sanctioned pumps remained high.

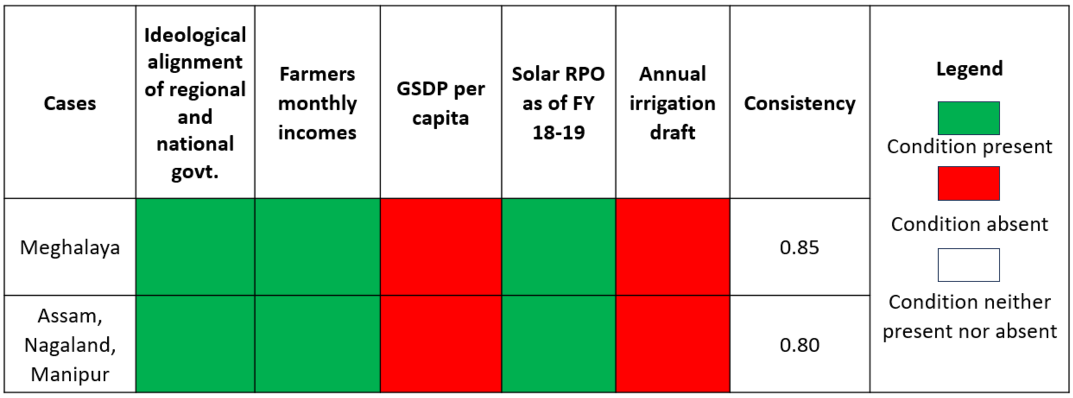

Figure 5.8: Observed solution pathways for negative performance with a 5% decrease in calibration thresholds

For negative performance, a 5% decrease in the calibration threshold resulted in one fewer solution pathway compared to the original thresholds. The pathway identifying West Bengal and Madhya Pradesh as negative performers was omitted. The overall solution consistency remained 0.80, with raw coverage at 0.44. Three of the five states identified as negative adopters under the original thresholds persist, with Manipur introduced alongside Meghalaya, Nagaland, and Assam.

The positive solutions exhibited minimal sensitivity to a 5% increase in calibration thresholds, retaining the same number of solution pathways. In contrast, the negative solutions showed greater sensitivity, with new pathways emerging. However, when the calibration thresholds are reduced by 5%, both positive and negative solutions become more sensitive, with some pathways being omitted.

6 Discussion and Conclusion

This chapter synthesizes the key discussion points and draws conclusions from the qualitative comparative analysis (QCA) and thematic analysis, shedding light on the underlying factors contributing to the varied performance of Component B of the PM KUSUM Yojana across states. Divided into two main sections—Discussions and Conclusions—the chapter first integrates the findings from both the QCA and thematic analysis. The discussions in section 6.1 will be broken down into two parts, section 6.1.1 explores how thematic insights and the QCA together provide insights into the state level differences of policy performance offering a comprehensive understanding of the factors influencing policy implementation outcomes. Following this, Section 6.1.2 expands the focus to broader discussions on policy disparities within Component B of the PM KUSUM Yojana, connecting these findings to larger trends in policy efficacy. Section 6.3 addresses each sub-research question and the main research question based on the findings. In Section 6.2, the study's results are compared with existing literature, highlighting both consistencies and unique contributions to the field. Finally, the chapter examines the implications of these findings for policy in Section 6.5, discusses limitations, provides targeted policy recommendations, and suggests future research directions in Section 6.6. This comprehensive analysis aims to inform ongoing efforts to refine and improve the PM KUSUM Yojana, emphasizing the study's broader academic and policy implications.

6.1. Discussion

The discussion delves into what are the possible reasons for adoption or non adoption of solar water pumps under component B of PM KUSUM.In subsection 6.1.1 the results of QCA and the pathways would be discussed further. Subsection 6.1.2 will then comment on the broader themes which help guide the discussion in the cases of positive or negative implementation of PM KUSUM component B.

6.1.1. Discussion on the results of QCA and thematic analysis

The adoption of solar water pumps under the PM KUSUM scheme is shaped by a complex interplay of economic resources, political alignment, and practical considerations such as irrigation demand. Significant irrigation demand or the need to replace diesel pump-sets sets up the foundation for the uptake of solar water pumps. As expected, states with strong economic resources—whether at the farmer or state level—demonstrate higher adoption rates, particularly when combined with a prior emphasis on solar energy initiatives. Even in the cases where there is no political alignment with the national government, adoption is often driven by either economically well-off farmers or robust state-level resources. This dynamic is evident in states like Maharashtra and Rajasthan, which have achieved notable success despite lacking political alignment with the national government. Interestingly though, even resource-constrained states can achieve adoption when regional governments align their objectives with national priorities, as seen in Uttar Pradesh. In such cases, political alignment often compensates for financial constraints, particularly to satisfy the demand for irrigation sources which is evident by the relatively higher irrigation needs of the region.

In contrast, states with little prior emphasis on solar energy can still witness growing demand through the initiatives of financially well-off farmers, particularly when supported by proactive state governments providing financial assistance. This dynamic is exemplified in Haryana, where substantial irrigation needs further amplify the demand for solar energy as a practical alternative. In such cases, the combination of farmer-led demand and state-level financial backing becomes a pivotal driver, enabling adoption even in settings with relatively lower interest in solar energy overall.

In states with lower adoption rates, a common obstacle is the lack of sufficient state financial resources to fund subsidies and to divert towards effective implementation. Limited budgets often compel these states to prioritize other objectives, leaving inadequate support for solar pump deployment. Even when farmers possess financial resources and political alignment exists, adoption can remain low due to minimal demand for solar pumps, as observed in Meghalaya. This is particularly true in regions with limited irrigation needs or a perceived lack of benefits from solar technology. Similarly, adoption remains constrained in states like Assam and Nagaland, where low farmer incomes and lower irrigation needs persist as reasons for non adoption of solar pumps despite ideological alignment with the national government. In such cases, financial constraints, inadequate state resources, and low interest in solar energy collectively with lower irrigation demand pose significant barriers for adoption of solar water pumps. Even in states like West Bengal and Madhya Pradesh, where irrigation demand is high, adoption is hindered by the combined effects of low farmer incomes, insufficient state resources, and lack of political alignment, preventing favorable policy outcomes.

Overall, while economic resources at both the farmer and state levels are critical, they are not the sole determinants of solar pump adoption. Political alignment, practical irrigation needs, and proactive efforts by state governments to provide financial support play pivotal roles in shaping adoption patterns. This complexity underscores the importance of tailoring policy strategies to regional contexts, highlighting the intricate balance required between economic capacity, institutional support, and local demand to ensure successful policy implementation under PM KUSUM.

6.1.2. Broader discussions

In a broader discussion of the positive and negative adoption of solar pumps under Component B of the PM KUSUM Yojana, several key findings emerge from the QCA and thematic analysis. Among all observations, one key theme becomes evident: outcomes are closely tied to the irrigation demand of farmers. This demand could stem from general irrigation needs or unreliable electricity access, which forces farmers to rely on diesel pump-sets to meet their irrigation requirements.

However, irrigation demand alone is insufficient to drive positive policy outcomes. For instance, West Bengal and Madhya Pradesh, despite having high irrigation demand, show poor performance under Component B of PM KUSUM due to a lack of political alignment—evidenced by the absence of ideological alignment between regional and national governments—and a shortage of financial resources for both farmers and the state. In these states, although irrigation demand exists, the lack of ideological alignment between regional and national governments likely results in lower prioritization of the scheme and slower access to necessary resources.

Political alignment and economic resources, either at the farmer or state level, are crucial for the successful adoption of the policy. In cases where irrigation demand exists, political alignment, whether through aligned objectives or governmental support, significantly influences positive outcomes. This is evident in Uttar Pradesh, where despite poor financial conditions for both the state and its farmers, the ideological alignment of national and state governments, along with a clear interest in solar energy, acted as key drivers of adoption.

Similarly, in Rajasthan and Maharashtra, the presence of irrigation demand, combined with strong state resources or higher farmer incomes, drove adoption even without ideological alignment with the national government. In Maharashtra, substantial state resources, its strategic deployment to increase subsidies, and strong support for the implementing agency compensated for the lack of political alignment, facilitating solar water pump installation to meet irrigation needs. In Rajasthan, the demand to replace diesel pump-sets due to unreliable electricity access, along with higher-income farmers willing to cover capital costs after subsidies, played a similar role in driving positive outcomes under Component B of

PM KUSUM.

Additional factors may also impact policy performance at the state level, primarily relating to the regional implementation approach and the involvement of key stakeholders. These include the effectiveness of the implementing agency, the institutional capacity established to ensure efficient policy deployment, and the coordination between departments. Furthermore, stakeholders such as financial institutions play a crucial role in facilitating credit access, while vendors contribute to the policy's success through implementation support and after-sales services.

Building on these insights, it becomes evident that while irrigation demand is a critical factor, it cannot guarantee the success of the scheme in isolation. For positive outcomes to be achieved under Component B of the PM KUSUM Yojana, irrigation demand must be coupled with either political alignment or the economic capacity of the region or its farmers. Initial examples of West Bengal and Madhya Pradesh demonstrate that high irrigation demand alone does not lead to successful adoption when these additional factors are absent. Conversely, in states like Uttar Pradesh, Rajasthan, and Maharashtra, the presence of either strong political alignment or sufficient economic resources has complemented irrigation demand, resulting in better policy performance and higher adoption rates.

6.2. Comparison to existing literature and academic contributions

To reflect on the findings of this study, it is essential to evaluate them against existing literature to highlight the significant contributions made by previous authors and to understand the additions this study makes to the body of knowledge. Several studies have examined policies for the adoption of solar irrigation. Among these, Adhikari, 2020 and Bassi, 2018 stand out as significant contributions. Both assessed policies for the adoption of solar energy for irrigation. Additionally, Agrawal and Jain, 2019 identified key determinants and strategies for solar water pump adoption, while Rathore et al., 2018 offered insights into the perspectives on solar water pumps in India and provided policy recommendations based on their findings.

Adhikari, 2020 conducted an ex-ante analysis of the solar adoption policy under the PM KUSUM scheme, utilizing an extensive literature review and consultations with sector experts to draw conclusions on the drivers and barriers of solar water pump adoption. Their study identified economic, social, environmental, and institutional drivers and barriers. Notably, some of the factors they highlight, such as farmer incomes, access to credit, and institutional coordination, align with those identified in the current study as factors affecting adoption.

Similarly, Bassi, 2018, also conducting an ex-ante analysis, employed a cost-benefit analysis to assess the economic and technical feasibility of solar water pumps, ultimately providing policy recommendations. Their focus was on quantifying the positive and negative effects of solar water pump adoption. However, the scope of their study was limited to the economic viability of the pumps, with a generalized approach toward India's eastern and western regions, which overlooks the intricate regional variations. Ultimately, Bassi, 2018 argued against the implementation of subsidies, suggesting that the social costs outweigh the welfare gains expected from such support.

However, both studies have certain limitations and points to be noted. Both the studies of Adhikari, 2020 and Bassi, 2018 are evaluations of policy before it was implemented. Adhikari, 2020 also did not consider the critical role of the state in the implementation process, the significance of subsidy support, or the political alignment within the implementing regions—factors that have proven essential in the current study. On the other hand, Bassi, 2018 focused more on the impacts of solar water pump deployment through subsidies rather than evaluating policy performance. Their study also did not account for state-level characteristics, which are vital determinants of policy impact.

Agrawal and Jain, 2019 explored the determinants of success for solar irrigation but did not specifically evaluate any particular policy. Their study focused on sustainability, dividing it into economic, social, and environmental aspects. They cited the importance of economic viability, after-sales service, and stakeholder coordination as crucial factors for the successful adoption of solar water pumps. However, this study did not assess any policy performance or consider how varying regional contexts could influence adoption rates.

Finally, Rathore et al., 2018 examined barriers to the adoption of solar water pumps in India before the implementation of the PM KUSUM policy. By conducting an extensive literature review, they identified several factors that hinder adoption, including lack of awareness, insufficient skilled workforce, fragmented policies, farmer economics, access to credit, and inadequate after-sales service. Although this ex-ante analysis offered valuable insights, it did not address the roles of institutions, stakeholders, state support, or the irrigation needs of farmers, all of which are significant to understanding solar water pump adoption in practice.

The policy briefs and reports published by various think tanks, which have provided consultation to the Government of India on the PM KUSUM policy, feature contributions from authors such as Pasupalati et al., 2022, Dutt and Krishnan, 2023, and Khanna, 2024. Pasupalati et al., 2022, in a study conducted for the World Resources Institute, draws insights from earlier policy implementations in Tamil Nadu, particularly relevant to Component C of PM KUSUM. These insights offer a reflection on why previous policies performed or underperformed prior to the roll-out of PM KUSUM. Key recommendations include the importance of appropriately sizing solar water pumps, establishing the right feed-in tariffs for the sale of surplus electricity, ensuring robust after-sales service, and creating a monitoring and evaluation mechanism to assess policy implementation impacts. Building on Pasupalati et al., 2022 findings, Dutt and Krishnan, 2023 developed a monitoring and evaluation framework to assess the impacts of Components A and C of PM KUSUM. While Pasupalati et al., 2022 study evaluates state-level policies, providing valuable insights into the factors influencing policy success or failure, it does not directly address the challenges of implementing a national policy at the state level. Factors such as state resources, political alignment, and irrigation demand play a significant role in policy uptake, yet the study does not extensively cover the role of vendors and their contribution to policy success.

Khanna, 2024, published in July 2024 by the Centre for Science and Environment (India), provides a more recent analysis of the policy's implementation across various states. The authors highlight factors such as the role of farmers, institutional support, access to free or subsidized electricity, and affordability issues that contribute to policy performance or non-performance. However, the report does not account for regional differences, particularly in terms of state finances and their capacity to fund subsidies and empower relevant departments. Moreover, the case studies focused on states with a clear demand for irrigation, failing to explore regions where low irrigation demand or difficulty in identifying demand has slowed policy implementation. Khanna, 2024 study complements the current research by incorporating on-ground opinions from farmers and providing an additional perspective on the successful implementation of PM KUSUM. This farmer-centered approach adds valuable insights into the practical realities of the policy's performance, reinforcing and augment the findings of the current study.

This study, as an *in media res* (into the middle of things) analysis of the PM KUSUM policy, provides valuable insights into regional differences in policy outcomes. By examining how the political and financial situations of state and sub-national governments, along with farmers' characteristics and institutional factors, interact in various contexts, it sheds light on the factors influencing solar water pump adoption in a policy context. While previous literature offers essential groundwork, this study extends these contributions with a more comprehensive analysis of state-level characteristics like finances, politics, and institutional roles, along with their combinations. Importantly, it fills a gap in academic research by examining policy performance across both agriculture and energy domains, with attention to regional influences that shape national policies like PM KUSUM. This study adds to academic literature by offering a deeper understanding of how regional fiscal resources and political alignment affect policy outcomes in agricultural solar adoption.

6.3. Conclusions

With growing global concerns over greenhouse gas emissions from conventional energy production, various sectors, including agriculture, are transitioning toward sustainable, low-emission energy solutions. This shift is particularly crucial in India, where agriculture serves as both an economic cornerstone and a significant energy consumer, largely reliant on fossil fuels. Policies like PM KUSUM aim to expedite this transition by promoting solar energy in agriculture, particularly through Component B, which supports the installation of solar water pumps.

Despite achieving significant installation numbers, Component B has shown notable disparities in adoption rates and policy performance across Indian states. These variations highlight the need to explore how state-specific contexts influence policy outcomes. Understanding these differences can uncover regional characteristics that either facilitate or hinder the transition to sustainable irrigation, offering insights into why certain states outperform others under the PM KUSUM policy. To analyze these regional differences, the research is structured around three sub-questions, each addressing a critical aspect of the main research question.

Research Sub-question 1: What factors could possibly affect the adoption of solar energy in agricultural irrigation practices, particularly in the context of policies addressing this adoption?

The adoption of solar energy in agriculture and irrigation depended on factors spanning socio-economic, energy, agricultural policy, and political domains. Economic factors, identified at both the meso and micro levels, seemingly play a pivotal role. At the meso level, regional per capita incomes and state economic resources for policy deployment were identified to be critical. At the micro level, farmer incomes, debt levels, technology costs, and payback periods were seen to impact adoption.

In the social domain, farmer characteristics such as age, education, internet access, and awareness levels were identified as possible determinants. Agricultural and energy-related factors include costs of existing energy inputs, on-farm energy demand, regional solar irradiance, farm size, cropping practices, farmers' experience, and water-related variables such as depth and requirements.

Political and institutional factors also significantly influence adoption. These include prior solar adoption, bureaucratic hurdles, inter-agency coordination, the existing institutional framework, and the ideological alignment between regional and national governments, which affects policy coherence and support.

Research Sub-question 2: How do combinations of these factors contribute to variations in policy outcomes for the solarization of irrigation across different states in India?

To analyze regional performance variations, 25 of 36 states and union territories were selected based on their participation in Component B of PM KUSUM. Policy performance was evaluated using the number of pumps installed as a percentage of those sanctioned, capturing both regional demand and resource allocation. Five conditions driving adoption were tested through QCA: farmers' monthly incomes (farmer economics), GSDP per capita (regional economics), solar RPO compliance as of FY 2018-19 (prior solar adoption), ideological alignment between state and national governments (political influence), and annual groundwater irrigation draft (irrigation demand).

The QCA revealed four solution pathways explaining positive performance in Maharashtra, Rajasthan, Uttar Pradesh, and Haryana, and three configurations explaining negative outcomes in Meghalaya, Assam, Nagaland, West Bengal, and Madhya Pradesh.
The QCA solutions revealed the trends of how irrigation demand from the region played a key role in the adoption of solar water pumps under component B of PM KUSUM. Though this irrigation demand alone wasn't sufficient for driving the positive adoption of policy. The solutions indicated that either political alignment of regional government or the financial resources either at the state level or farmer levels could have an influence on the adoption rates. These pathways highlight how specific combinations of factors influence adoption, warranting further exploration through qualitative thematic analysis.

Research Sub-question 3: What explains the different combinations of factors influencing regional adoption of solar water pumps under the policy?

The QCA offered insights into factor combinations influencing policy outcomes, but qualitative analysis provided a deeper understanding of how individual and multiple factors interact to have an influence on policy outcome. Semi-structured interviews with policy experts and consultants, followed by thematic analysis, identified recurring themes.

The analysis revealed that political alignment can influence state-level objectives, driving stronger policy support in some cases. However, it was mentioned in by some interviewees that alignment alone was not universally decisive; some states pursued solar adoption independently of political alignment. Prior solar adoption and pilot programs emerged as critical enablers, with institutional capacity built during pilots positively influencing outcomes.

Thematic analysis revealed that state resource allocation, guided by government objectives, affects the financial and human resources available to implementing agencies, shaping policy success. Irrigation demand, inferred from annual groundwater draft in QCA, was also influenced by high diesel pump usage or unreliable electricity access, even in areas with low groundwater requirements as indicated in the thematic analysis. Farmers' incomes, though a significant factor, did not necessarily impede adoption in states where farmer incomes are lower and the state government can support the subsidy with robust financial support mechanisms. These findings clarify the reasoning behind the combinations of factors observed in regional policy performance.

Beyond demand drivers and adoption incentives, thematic analysis uncovered additional factors that, while difficult to quantify for the QCA, influence policy outcomes. These include implementation practices and the role of stakeholders beyond government and farmers, such as vendors and financial institutions.

Interviewees emphasized that implementing departments with well-coordinated setups, streamlined procedures, and effective complaint resolution mechanisms can enhance farmer confidence and encourage adoption. Vendors also play a critical role; timely payments and reliable after-sales service build trust, while states with lower demand may struggle to attract vendor participation. Access to credit remains a significant barrier, hindered by bureaucratic challenges, complex procedures, competing financial priorities, and poor coordination between banks and ministries, compounded by concerns over farmers' credit reliability.

With the insights gained the central question of the study was addressed:

Why are there disparities in the performance of the policy aimed at replacing diesel pumps with solar irrigation systems across states in India?

Disparities in the adoption of solar irrigation systems under Component B of PM KUSUM are closely linked to irrigation demand, complemented by either political alignment or economic resources. Irrigation demand—whether driven by general irrigation needs or unreliable electricity access leading to diesel pump use—establishes a baseline for adoption but is insufficient alone to generate positive outcomes.

For instance, states like West Bengal and Madhya Pradesh, despite high irrigation demand, show low policy performance due to limited political support and inadequate financial resources. In contrast, states where irrigation demand is reinforced by political alignment or economic resources exhibit significantly better outcomes. In Uttar Pradesh, political alignment between state and national governments drove favorable policy outcomes despite constrained financial resources. Similarly, in Rajasthan and Maharashtra, the combination of irrigation demand with either strong state resources or higher farmer incomes facilitated successful adoption, despite the lack of political alignment of the regional government with the national government through the duration of the scheme.

Effective implementation further enhances policy success. Institutional capacity, inter-departmental coordination, and stakeholder involvement, including financial institutions and vendors, create an environment conducive to adoption. Credit facilitation and reliable after-sales support strengthen policy uptake. Together, these findings emphasize that irrigation demand must be supported by at least one enabling factor—political alignment or economic resources—for the PM KUSUM policy to achieve widespread success.

6.4. Limitations of Study

This study has certain limitations that could be addressed in future research on policy performance in renewable energy. First, the number of explanatory variables was restricted to five to ensure meaningful analysis. For best practices of QCA, in medium-N samples, where k represents the number of causal condition variables, the maximum sample size should not exceed k^2. Pappas and Woodside, 2021 recommend using around 5 to 7 variables as a best practice. While qualitative analysis partially compensates for this limitation, additional explanatory variables could provide a more nuanced understanding of regional policy performance in national energy and agricultural contexts. Another limitation lies in capturing demand for solar water pumps. While irrigation needs and the prevalence of diesel pump-sets serve as proxies, these variables do not fully represent the complexities of demand based on regional irrigation practices. This gap is partly addressed by qualitative insights from experts, who shed light on demand drivers in well-performing regions.

In calibrating the QCA variables, this study adhered to the guidelines of Pappas and Woodside, 2021 as outlined in Table 4.1. However, as Parente and Federo, 2019 notes, setting calibration thresholds can lack a strong theoretical foundation, potentially introducing subjectivity. Acknowledging this limitation, the study relies on rank orders and percentiles for calibration, as theoretical cut-off points are not available for all datasets. Future studies could adjust these thresholds based on sound theoretical justifications to assess the impact on results.

Lastly, time constraints limited engagement to insights from policy experts and consultants, who offered a range of perspectives based on their policy involvement. Although this limits firsthand input from farmer organizations, ministry officials, and solar pump vendors, their views are nonetheless represented through secondary information derived from experts' interactions with these stakeholders. Expanding input from these groups in future studies could still deepen the qualitative analysis and provide a deeper understanding of policy effects.

6.5. Policy recommendations

Based on the findings of the thesis, the following policy recommendations are proposed to enhance the performance of future iterations of the PM KUSUM policy, particularly Component B:

- Strengthen the existing model of 50% central financial assistance to provide greater support to states with limited fiscal resources, particularly in regions where farmers face financial constraints. Extending CFA in these areas could lower barrier of entry for financially restrained farmers by making solar water pumps more affordable.
- Explore the possibility of expanding the CFA to partially or fully cover the state's subsidy share in specific cases where state financial resources are exceptionally limited. This measure would help alleviate financial pressures on states and improve adoption rates in under-resourced regions.
- Encourage states with lower demand to collaborate with neighboring regions to aggregate larger orders. These combined orders can create economies of scale, making procurement more appealing for vendors and boosting adoption in areas with limited demand.
- Foster partnerships with financial institutions to simplify credit access for farmers by reducing paperwork, minimizing bureaucratic hurdles, and enhancing coordination.
- Expand the existing online platform to include streamlined loan facilitation features, allowing farmers easier access to financing with clear guidance on requirements and improved responsiveness from financial institutions.
- Identify and address institutional barriers within the implementing agencies, including specific process bottlenecks, with the goal of progressively improving efficiency as the scheme unfolds.

Enhancing national-level subsidy support, facilitating credit access, refining implementation processes and aggregating demand across states can significantly improve the uptake of Component B of PM KUSUM, particularly in states with lower adoption rates, ultimately supporting broader scheme success across India.

6.6. Future scope of research

The current study, while addressing state-level variations in the performance of policies aimed at promoting solar water pump adoption, offers a foundation that could be further developed to explore additional aspects of policy deployment at the intersection of the energy and agriculture sectors. Future research could complement this work by examining other policies in similar domains to draw comparisons and identify consistent or contrasting factors that influence performance across different contexts. For instance, a comparative study could investigate a similar policy, analyzing its performance alongside the findings of this study to illuminate contextual drivers and barriers to success.

Expanding on this, a farmer-level study similar to V. Kumar et al., 2020 and Sunny et al., 2022 could help identify characteristics of farmers inclined to adopt solar water pumps, particularly when tested across diverse regions to capture potential regional differences in adoption behaviors and the social dynamics influencing these choices. Another research direction might involve developing a metric to quantify farmer demand more precisely, providing a basis for more targeted and responsive policy adaptations.

In addition, research could focus on projecting the long-term impacts of the policy, especially concerning groundwater over-extraction in response to increased solar pump usage. This could involve a monitoring framework similar to that proposed by Dutt and Krishnan, 2023 to systematically track and assess the broader environmental effects of solar pump installations. Following the completion of the policy's initial phase, a longitudinal study could evaluate shifts in policy outcomes over time (2019-2026), exploring whether adoption rates and regional performance metrics evolve due to evolving dynamics within each region.

To conclude, the adoption of solar irrigation systems under Component B of the PM KUSUM Yojana varies significantly across Indian states due to an interplay of irrigation demand and at least one regional enabling factor, such as political alignment or economic resources, either at the state or farmer level. While irrigation demand—often driven by agricultural needs or unreliable electricity access—provides a foundation, it alone does not ensure policy success. Positive outcomes emerge when this demand is supported by the state's commitment to renewable energy initiatives or by economic resources, either through farmer-level financial capacity, such as credit access and the ability to cover upfront costs, or state-level resources that enable large-scale investment and prioritization. Effective implementation is further enhanced by institutional coordination across departments, support from financial institutions, and vendor involvement, creating a favorable environment for adoption. These findings highlight that irrigation demand, combined with political alignment or economic resources at either the state or farmer level, is crucial for achieving the policy's success, emphasizing the need for regional adaptability within the PM KUSUM Yojana framework.

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A

Appendix A

A.1. Description of components A and C

The description of component A and C of PM KUSUM scheme is provided here. These components are focused on setting up of decentralized solar power plants in agricultural lands (component A) and setting up of grid connected solar pumps(IPS - component C) or solarizing agricultural electricity feeders(FLS - component C).

Component A

Under component A of the PM KUSUM scheme the farmers can avail an option to set up solar energy based power plants with capacity range of 500 KW to 2 MW(MNRE, 2019). The subsidy under the component can be availed as an individual farmer or a farmer collective. The solar power generated will be purchased by DISCOMs at a feed-in-tariff [FiT] determined by respective State Electricity Regulatory Commission [SERC]. This component also gives an option to the farmer to lease their land to a solar developer who has the rights to the sale of power from energy generated but provides the farmer with rent(Rahman et al., 2021). This particular component can also ”improve the power supply situation in the locality, especially in areas with poor quality supply, thus improving access to electricity for other farmers”(MNRE, 2019; Rahman et al., 2021). The DISCOMs also stand to benefit as the power procurement cost reduces along with fulfilling their RPOs while cutting down on transmission and distribution losses(Rahman et al., 2021). The scheme encourages the setting up of solar plants in barren and fallow lands in particular maximizing the utilization of land owned by farmers(agricultural or otherwise) under component A(MNRE, 2019).

Component C

This component itself can be divided into two parts: Individual Pump Solarization[IPS] and Feeder Level Solarization[FLS]. Under the IPS configuration: Farmers who have grid connected electric pumps are encouraged to adopt grid connected solar pumps. Solar photovoltaic capacity of up-to two times of the electric pump capacity is allowed. The grid connected nature enables the farmer to sell back excess electricity to the DISCOM. Similar to component B, 30% of the capital cost is provided as central financial assistance, with an additional 30% contribution from the state government. Farmers are responsible for covering the remaining 40% of the capital cost. However, they have the option to avail themselves of a loan financing option to cover 30% of the 40%. This leaves only 10% of the capital cost to be directly paid by the farmer at the time of installation. In some states/union territories the central financial assistance is increased to 50% leaving the farmer only needing to cover 20% of the capital costs. The inspiration for the scheme comes through Gujarat’s SKY scheme(Pasupalati et al., 2022).

In the case of FLS component of the scheme, the states can solarize agricultural feeders instead of solarizing each pump(MNRE, 2019). Where agriculture feeders are not separated, loan for feeder separation may be taken from NABARD or PFC/REC at a favourable interest rate. According to MNRE, 2019, ”The farmers will get day-time reliable power for irrigation free of cost or at tariff fixed by their respective state”. The Mukhyamantri Saur Krushi Vahini Yojana[MSKVY] scheme executed in Maharashtra stood as an example for the FLS part of component C(Gambhir et al., 2021).This model, unlike the IPS, ”does not need to have direct involvement of farmers”(Rahman et al., 2021). Through both these parts of component C, the state government aims to reduce the power subsidy burden by solarizing existing feeders and pumps(MNRE, 2019). It also provides the farmers with daytime access to electricity, while giving them an opportunity to gain additional income especially under the IPS part of the component(Rahman et al., 2021). Power quality is also aimed to be improved with possibility of uninterrupted power supply. In component C, ”the grid-connected solar pumps will be provided with a capacity up to 7.5 HP with doubled the solar PV capacity, as the extra power generated from the solar panels can be sold to the distribution company giving extra income to the farmers”(MNRE, 2019).

A.2. Search terms used for identification of factors which influence solar adoption in agriculture

The literature to help identify the factors which influence adoption of solar in agricultural contexts, constituted of a search through scopus database with a combination of keywords to narrow down key peer reviewed academic literature. This is supplemented with a primary search for policy think tanks who study India's policy regarding agriculture, irrigation and energy and their website archives by searching for the reports which address policy for solarization of agriculture. Peer reviewed academic sources were sorted by the usage of a few key words and the combination of key words. Some of the sources were further explored from the references in certain key peer reviewed academic sources. The prompts used to filter the key academic papers are:

- ”solar” AND ”irrigation” AND (”adoption” OR ”factors”)
- ”policy” AND ”solar” AND ”agriculture” AND (”assessment” or ”analysis”)
- ”solar” AND ”agriculture” AND ”factors” AND ”adoption”
- ”energy” AND ”agriculture” AND ”factors” AND ”adoption”
- ”solar” AND ”factors” AND ”regional” AND ”adoption”

A.3. Literature on factors identified

Author, Year, Scope	Type of Analysis	Factors Determined
Tate et al., 2012, United Kingdom, 2000 farmers	Principal component Analysis	Education, age, land ownership, funding, profitability, size of farm, agricultural income, farmers' existing debt
Beckman and Xiarchos, 2013, California, USA, 8569 farmers	Heteroskeadastic ordered binary model	Electricity price, internet access of farmers, prior adoption by farmers, farmer experience, farm type, farmer income, age, education, regional policies supporting funding, capital investment
Ge et al., 2017, Scotland, 20946 farms	Logit Model	Diversification of farms, energy demand of farms, solar irradiance, age of farmer, farm land used for cropping, farm size
Schaffer and Düvelmeyer, 2016, 71 counties in Bavaria, Germany	Spatial Regression Analysis	farm size, farm type, age, education, agricultural structure, neighborhood effects
Sutherland et al., 2016, 2416 agricultural holdings, Scotland	Structured Equation Modelling	Age, education, experience of farmer, information access, farm size, ownership status of farm, income of farmers, subsidy availability
Borchers et al., 2014, 8569 farms, USA	Multilevel logit model	farm size, farmer income, internet access, farmer experience, solar irradiance, subsidies and incentive availability, regional per capita income
Kata et al., 2021, Poland, 226 farmers	Logistic regression and Multiple regression	economic cost, profitability, energy demand, price of energy/electricity, prior adoption of renewable energy, farm size, farm type, farmer income, age, awareness
Ruiz-Fuensanta et al., 2019, 428 farms, Spain	Multilevel logit model	farm size, farm type, education, prior adoption, investment in R&D, market pull created by subsidies and grant availability
Agir et al., 2023, 16 farmers and 3 agricultural bureaucrats, Turkey	Qualitative analysis	institutional setting, co-ordination of agencies, bureaucracy, cost savings, awareness, capital cost, income generation, policy-mix, farmers income, ease of business
Li et al., 2021, 643 farmers, China	Bi-variate probit model	financial viability, awareness, age, subsidy support, education, farmer experience, production specialization , farm size, ease of use, information availability, willingness of government

Wagner et al., 2024, 214 farmers, Germany	Factor analysis and binary logistic regression	risk tolerance (related to farmer income), awareness, education, information available, climate change impact, financial incentives, bureaucracy
Moerkerken et al., 2023, 279 farmers, Netherlands	Multiple regression analysis	awareness, education, farm ownership, payback period, policy setting, financial incentives
Powell et al., 2021, 24 stakeholders and experts, Australia	Adoption and Diffusion Outcome Prediction Tool (ADOPT) framework	economic and environmental benefits, ease of use, awareness, risk tolerance (connected to farmer income), farmer income, policies and subsides
Sunny et al., 2022, 405 farmers, Bangladesh	Logit model	farmer experience, knowledge, awareness, subsidy and incentives, soil fertility, farmer income, neighbourhood effects
Rana et al., 2021, 140 farmers, Bangladesh	Probit model analysis	education, extension services, credit access, farm size, farmer income
V. Kumar et al., 2020, 510 farmers, Punjab, India	Multiple regression analysis	economic benefits, compatibility, awareness, incentives and subsidies, capital and maintenance costs, payback period, financing
Agrawal and Jain, 2019, 12 stakeholder interviews, India	Qualitative analysis	Crop type, water depth, solar irradiance, capital costs, awareness, after sales service.

Table A.1: Summary of findings from literature of factors identified closely co-relatinng to adoption of solar in agricultural context

B

Appendix B

B.1. Distribution plots of Raw Data

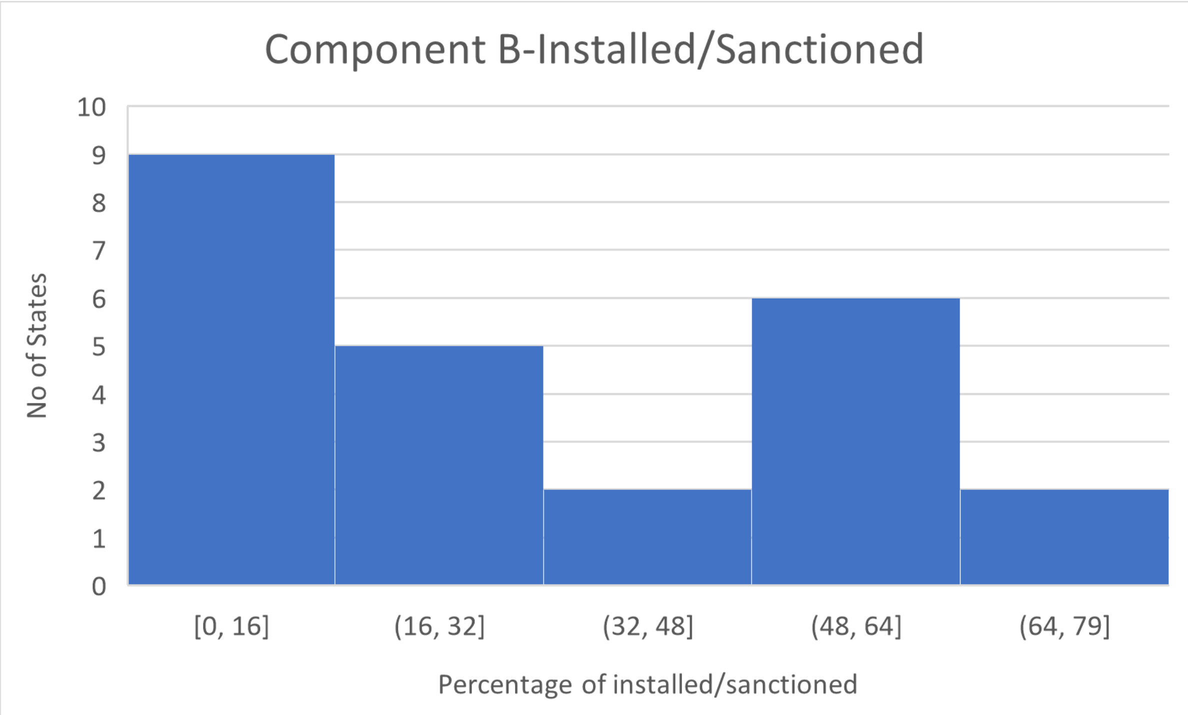

Figure B.1: Component B outcome distribution

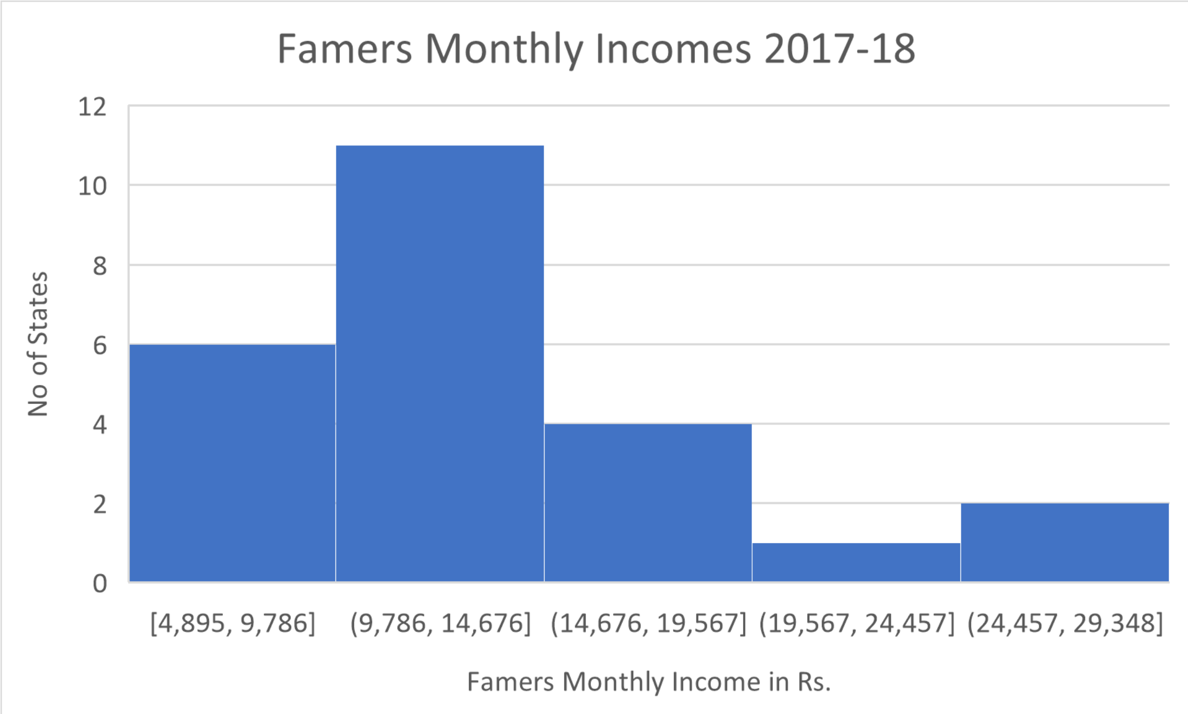

Figure B.2: Farmer monthly income distribution

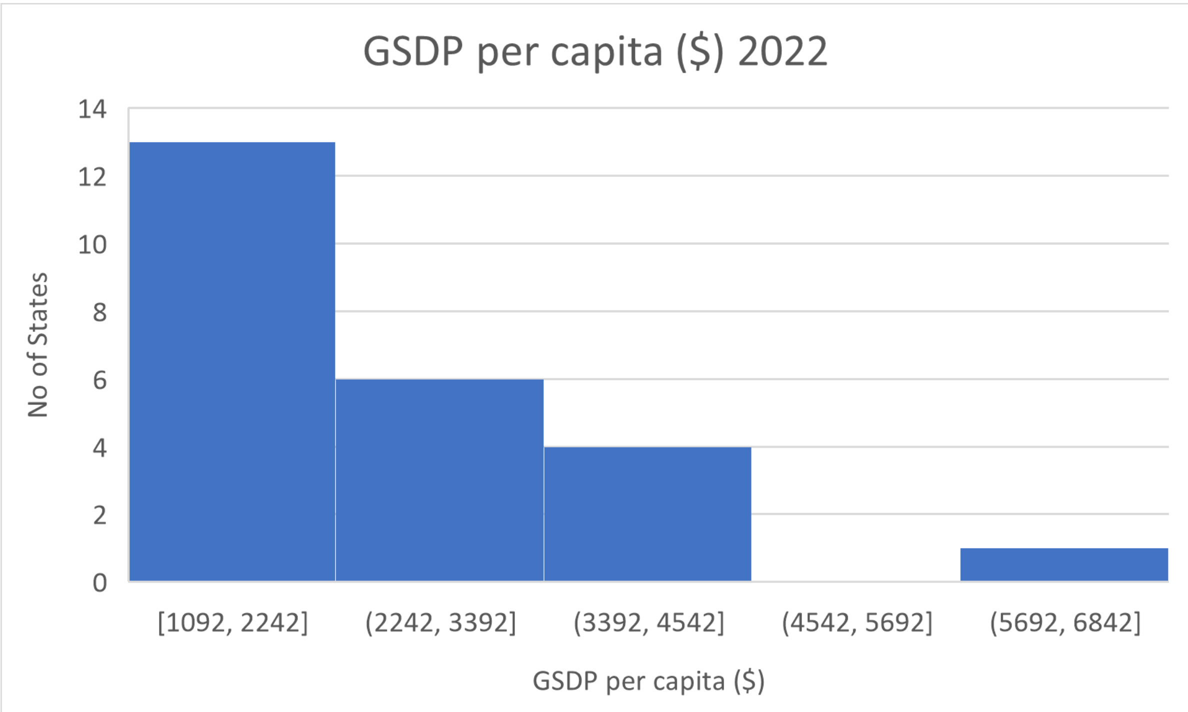

Figure B.3: GSDP per capita distribution plot

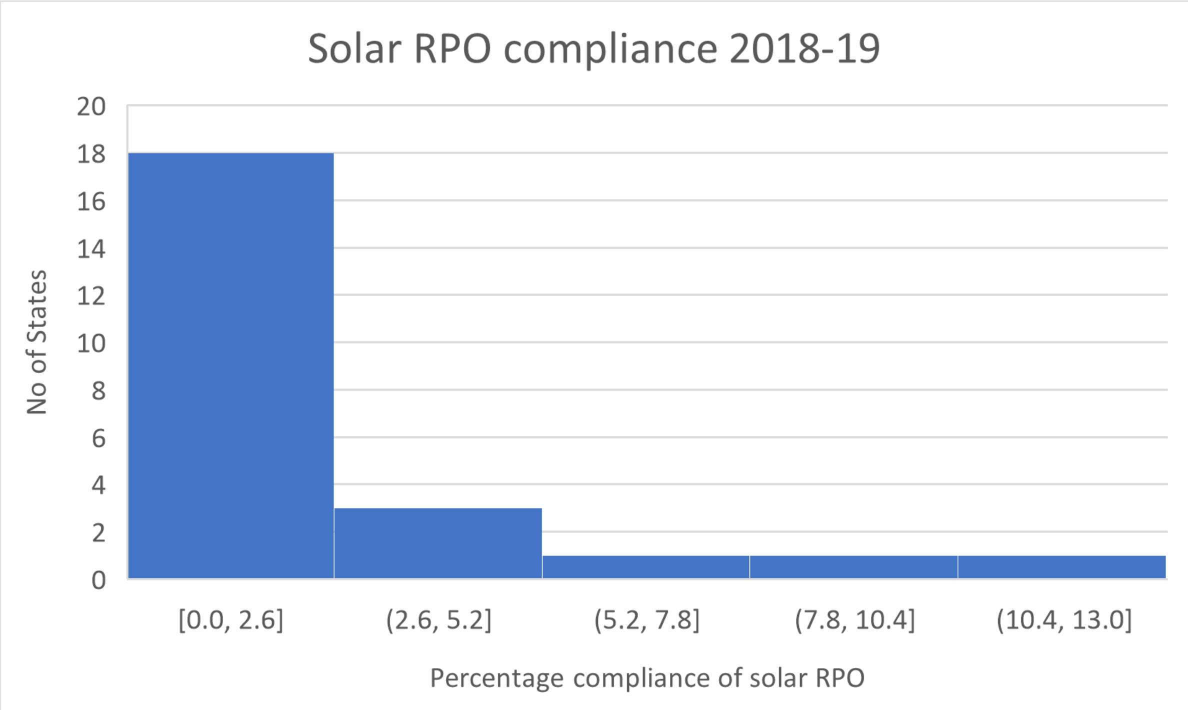

Figure B.4: RPO distribution plot

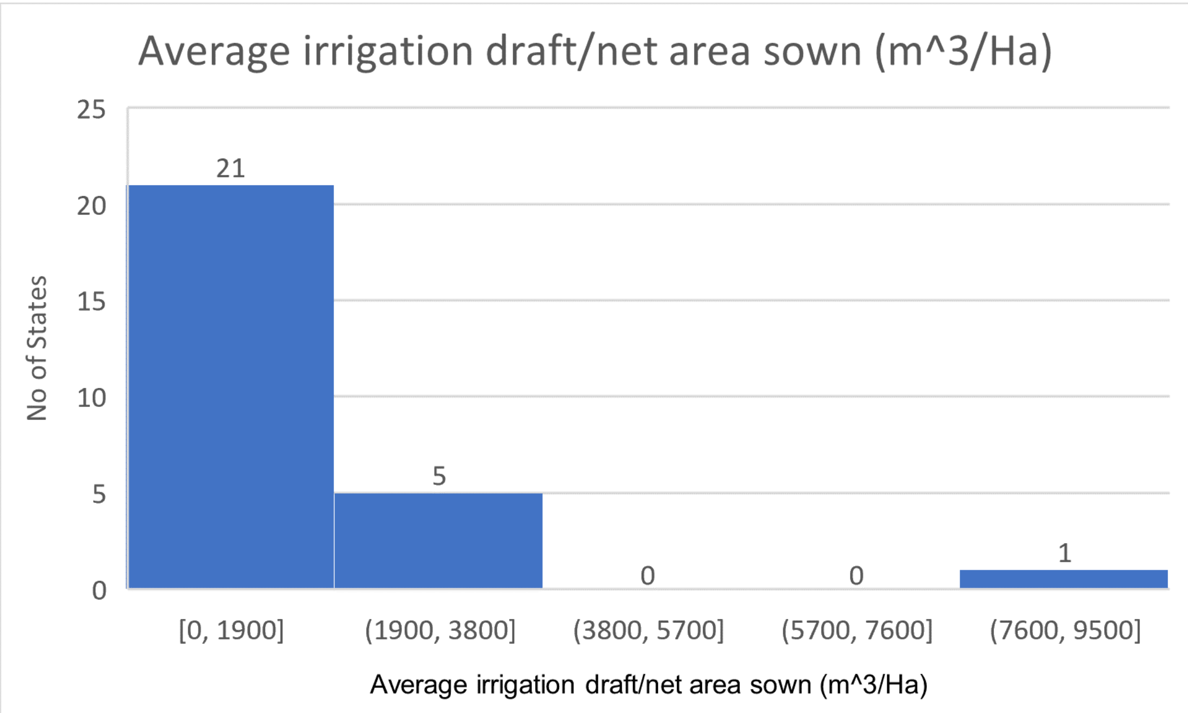

Figure B.5: Annual irrigation draft per net area sown distribution plot

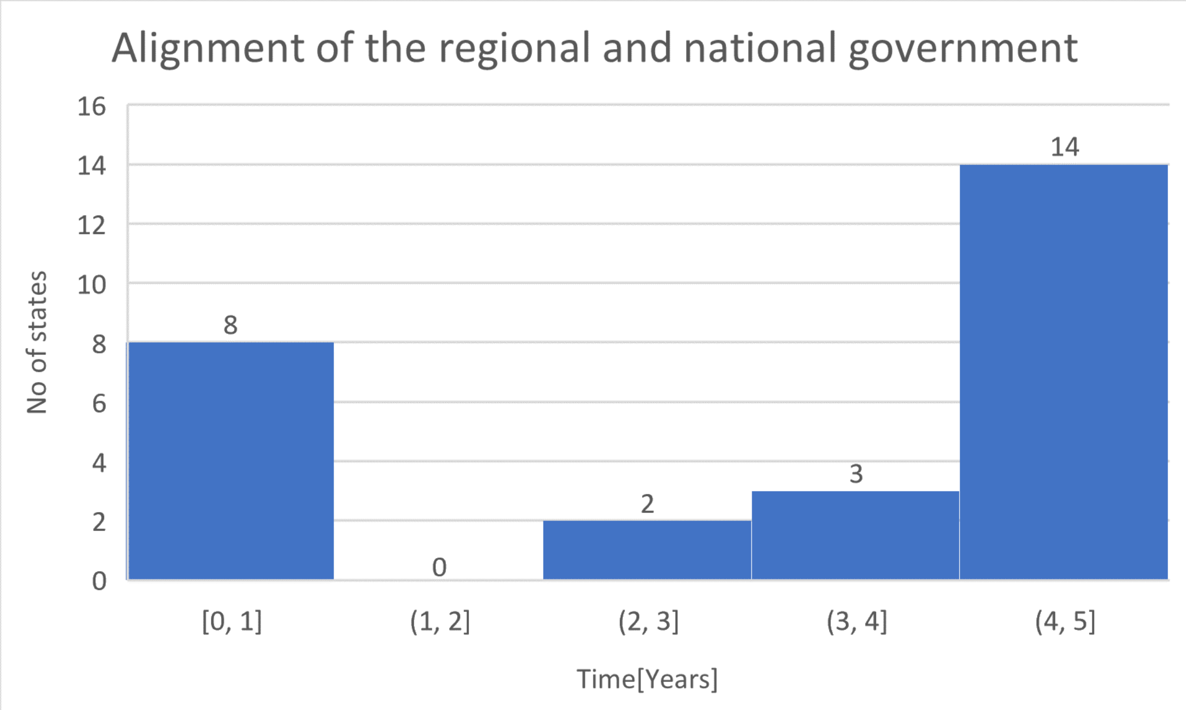

Figure B.6: Ideological alignment of national and regional government

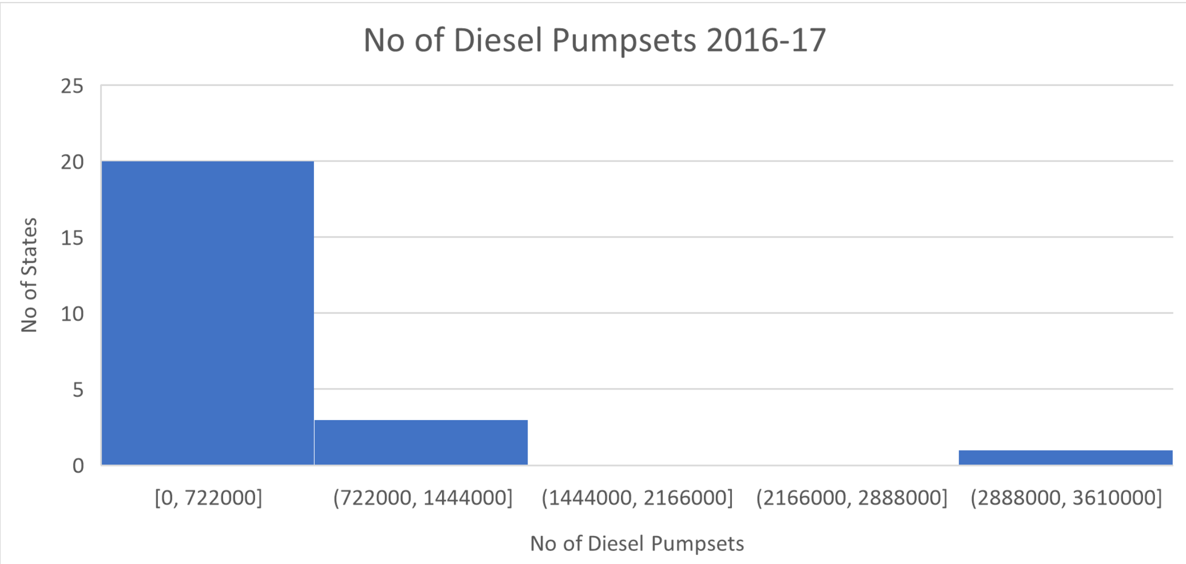

Figure B.7: No of Diesel Pump-sets distribution plot

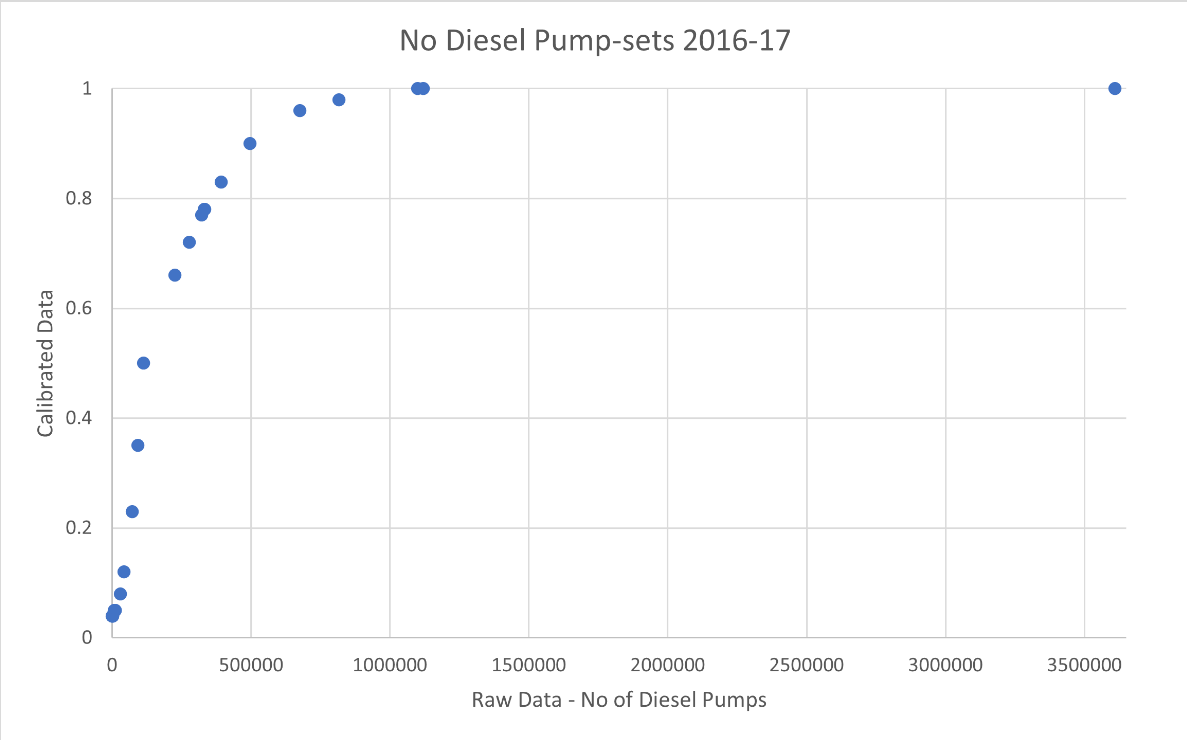

Figure B.8: No of Diesel Pump-sets calibrated plot

B.2. Raw Data for component B variables

States	Installed vs sanctioned (%)	Annual ground-water irrigation draft per net area sown (cubic m/ha)	Diesel pump-sets	Solar RPO compliance (%) in FY 18-19	GSDP per capita ($)	Farmer monthly incomes in Rs.	Alignment of national and state govt. over 5 years
AR	54.29	12.4	2300	0.21	2960	19225	5
AS	0	723.2	92100	0.09	1518	10675	5
CG	0	979.88	113500	1.3	1777	9677	0
GA	8.78	157.48	11800	0	6842	18511	5
GJ	59.78	1287.93	674800	2.09	3577	12631	5
HP	50.24	380.23	1900	0.13	3086	12153	3.75
HR	67.78	2899.47	322000	0	3841	22841	5
J&K	31.34	271.74	29500	0	1927	18918	5
JH	41.02	700.3	330600	0.25	1202	4895	0.75
KA	3.32	838.21	334200	12.97	3797	13441	3.75
KL	8	570.02	16000	0.63	3439	17915	0
MH	34.23	918.32	393300	3.68	3227	11492	2.4
ML	3.16	118.58	11200	1.46	1510	29348	5
MN	52	7.32	100	0.3	1323	11227	5
MP	12.33	1096.84	11,00,000	0	1733	8339	4
MZ	0	0	0	0.02	2958	17964	4.75
NL	24.53	5.18	8100	0	1872	9877	5
OR	79.49	1316.1	495500	1.01	1899	5112	0
PB	24.44	7949.59	226700	3.37	2504	26701	0
RJ	29.62	800.65	11,20,000	6.13	1982	12520	0.25
TN	62.98	2797.43	278600	9.92	3513	11924	2.15
TG	0	1202.97	56200	3.42	3875	9403	0
TR	27.77	78.43	71900	0	1985	9918	5
UK	5.59	1014.49	43000	1.1	3080	13552	5
UP	47.75	2522.61	36,10,000	4.08	1092	8061	5
WB	0	2052.25	817000	0.09	1799	6762	0

Table B.1: Raw data of the Installed/Sanctioned percentage and the variables to be tested

B.3. Calibrated data for component B variables

States	INSB	AID	RPO	GSDP	FMI	ALI	DIE
AR	0.96	0.04	0.29	0.86	0.96	0.95	0.04
AS	0.04	0.39	0.11	0.04	0.25	0.95	0.35
CG	0.04	0.6	0.71	0.19	0.12	0.05	0.5
GA	0.11	0.06	0.05	1	0.95	0.95	0.05
GJ	0.98	0.78	0.84	0.95	0.58	0.95	0.96
HP	0.94	0.14	0.15	0.89	0.52	0.35	0.04
HR	0.99	1	0.05	0.97	0.99	0.95	0.77
J&K	0.62	0.09	0.05	0.4	0.95	0.95	0.08
JH	0.83	0.37	0.38	0	0	0.07	0.78
KA	0.06	0.5	1	0.97	0.66	0.35	0.78
MH	0.7	0.56	0.96	0.91	0.41	0.18	0.83
ML	0.06	0.05	0.74	0.03	1	0.95	0.05
MN	0.95	0.04	0.5	0.01	0.35	0.95	0.04
MP	0.16	0.67	0.05	0.14	0.04	0.38	1
MZ	0.04	0.03	0.06	0.86	0.93	0.5	0.04
NL	0.43	0.03	0.05	0.31	0.14	0.95	0.05
OR	1	0.79	0.66	0.35	0	0.05	0.9
PB	0.43	1	0.94	0.73	1	0.05	0.66
RJ	0.58	0.46	1	0.49	0.56	0.05	1
TN	0.98	1	1	0.95	0.5	0.16	0.72
TG	0.04	0.71	0.95	0.97	0.11	0.05	0.16
TR	0.52	0.05	0.05	0.5	0.14	0.95	0.23
UK	0.08	0.62	0.67	0.89	0.67	0.95	0.12
UP	0.92	0.99	0.97	0	0.03	0.95	1
WB	0.04	0.97	0.11	0.21	0.01	0.05	0.98

Table B.2: Calibrated Dataset

B.4. Truth Table for Component B positive and negative outcomes

ALI	FMI	GSDP	RPO	AID	number	INSB	cases	Raw consistency
1	0	0	1	1	1	1	UP	0.927536
0	1	0	1	0	1	1	RJ	0.923077
1	1	1	0	1	1	1	HR	0.87907
0	0	1	1	1	1	1	MH	0.838188
0	0	0	1	1	2	0	CG, OR	0.783051
0	0	0	0	0	1	0	JH	0.780952
1	1	0	0	0	1	0	J&K	0.77459
0	1	1	1	1	1	0	PB	0.758112
1	1	1	1	1	2	0	GJ, UK	0.678161
1	0	0	0	0	2	0	AS, NL	0.676737
0	1	1	0	0	1	0	HP	0.674699
1	1	0	1	0	1	0	ML	0.614286
1	1	1	0	0	2	0	AR, GA	0.601542
0	0	0	0	1	2	0	MP, WB	0.508361

Table B.3: Truth table component B positive outcomes

ALI	FMI	GSDP	RPO	AID	number	∼INSB	cases	raw consistency
0	0	0	0	1	2	1	MP, WB	0.792642
1	0	0	0	0	2	1	AS, NL	0.782477
1	1	0	1	0	1	1	ML	0.771429
0	1	1	1	1	1	0	PB	0.722714
1	1	0	0	0	1	0	J&K	0.713115
1	1	1	0	0	2	0	AR, GA	0.699229
0	1	1	0	0	1	0	HP	0.698795
1	1	1	1	1	2	0	GJ, UK	0.685824
0	0	0	1	1	2	0	CG, OR	0.667797
0	0	0	0	0	1	0	JH	0.647619
0	0	1	1	1	1	0	MH	0.605178
1	0	0	1	1	1	0	UP	0.502415
1	1	1	0	1	1	0	HR	0.460465

Table B.4: Truth table component B negative outcomes

B.5. Replacing the variable representing irrigation demand with the number of diesel pump-sets

In this section, the irrigation demand variable is replaced by the total number of diesel pump-sets that need to be replaced. This variable serves as a proxy for the demand for solar water pumps to substitute the existing irrigation pump-sets. The information on the number of diesel pump-sets is sourced from the All India Report on Input Survey 2016-17, published by the Agricultural Census Department of the Ministry of Agriculture and Farmers Welfare in 2021 (AgriCensus, 2021). The calibrated variable for the number of diesel pump-sets per region is represented as DIE. The distribution was left-skewed, and therefore, the calibration thresholds were set at the 80th percentile, 50th percentile, and 20th percentile for the inclusion, crossover, and exclusion points (refer to figure B.7 for the distribution)(Pappas and Woodside, 2021). The calibrated dataset is presented in Appendix B.8.

The consistency threshold of the solution for positive outcomes of the policy with this variable introduced was maintained at 0.8. The positive solution is shown in the figure B.9. The overall solution consistency of the positive solution is 0.86 with a raw coverage of 0.48.

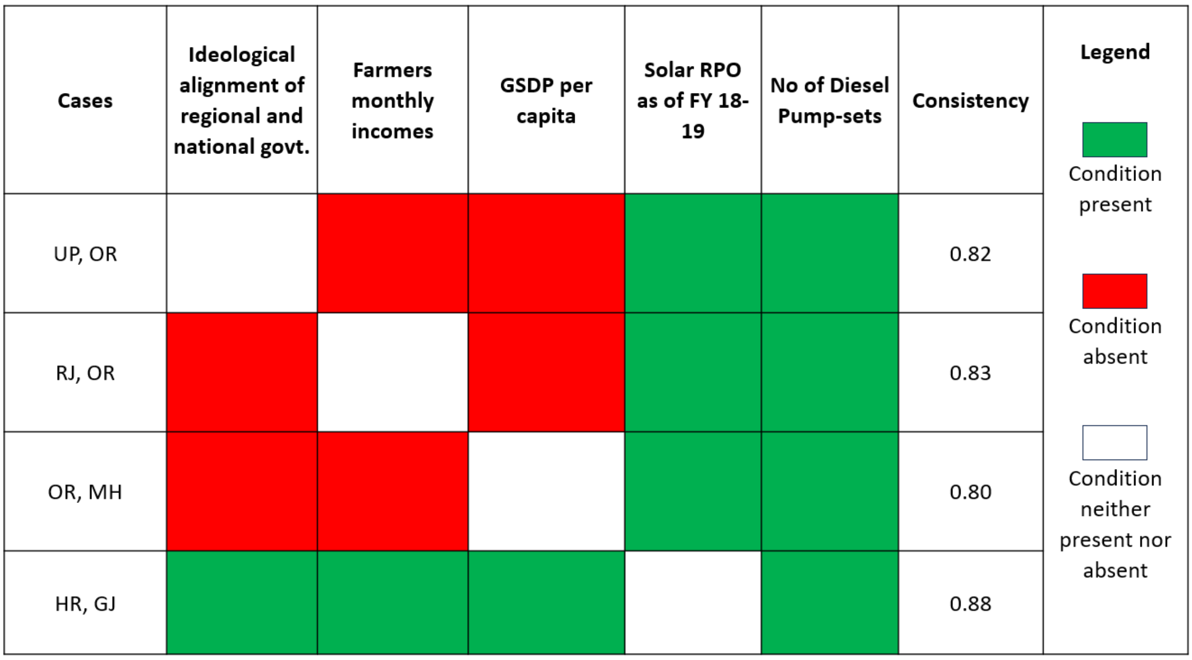

Figure B.9: Solution outcomes of the positive outcomes where the irrigation demand is replaced with number of diesel pump-sets

Four of the six states identified as positive adopters under Component B of PM KUSUM were also present in the solution outcomes when the variable tested was irrigation demand, measured by the annual groundwater irrigation draft. These states all exhibit high usage of diesel pump-sets to meet their irrigation needs. This is true even for Rajasthan, where irrigation demand is relatively low, but diesel pump-sets are widely used due to limited electricity access in many regions. The other two states showing positive performance, in terms of the percentage of installed pumps relative to sanctioned pumps, are Orissa and Gujarat.

Orissa demonstrates positive performance in three solution pathways, showing similarities with Maharashtra, Uttar Pradesh, and Rajasthan. The state has a pre-existing history of solar energy adoption, similar to these three states. This effort is further supported by Orissa's high usage of diesel pump-sets, which the state actively seeks to replace with solar water pumps, as seen in the other cases. Orissa shares commonalities with Uttar Pradesh in terms of limited resources, both for the farmers and the state, as both are financially weaker compared to their peers. However, while Uttar Pradesh benefits from ideological alignment with the national government, Orissa has not been aligned with the national government for most of the scheme's implementation period. Similarly, Orissa and Maharashtra both face non-alignment with the national government and have low farmer incomes. However, unlike Maharashtra, which is financially well off compared to other states, Orissa does not share this financial advantage. Finally, Orissa resembles Rajasthan in its lack of financial strength compared to its peers and its non-alignment with the national government. However, it differs from Rajasthan in terms of farmers' financial standing, as Orissa's farmers do not enjoy the same level of financial stability as those in Rajasthan.

In the case of Gujarat, which shares similarities with Haryana, the combination of higher irrigation needs and comparatively higher monthly farmer incomes has incentivized greater adoption of solar energy. Additionally, Gujarat has the financial resources to support subsidies, which, along with the region's significant usage of diesel pump-sets, has contributed to positive adoption of solar water pumps. The state's alignment with the national government during the scheme's implementation could explain the push for solar water pumps, with the state's objectives aligning as a reflection of its ideological alignment with the central government. The key distinction between Gujarat and Haryana is Gujarat's pre-existing adoption of solar energy, evidenced by it having the largest installed solar capacity in India(MNRE, 2023).

The consistency threshold of the solution for negative outcomes of the policy with this variable introduced was reduced to 0.75 which is the minimum mandated value for meaningful result generation as recommended by Pappas and Woodside, 2021 since there were no solutions generated when testing the calibrated data with a consistency threshold of 0.8. The negative solution is shown in the figure B.10. The overall solution consistency of the positive solution is 0.75 with a raw coverage of 0.49.

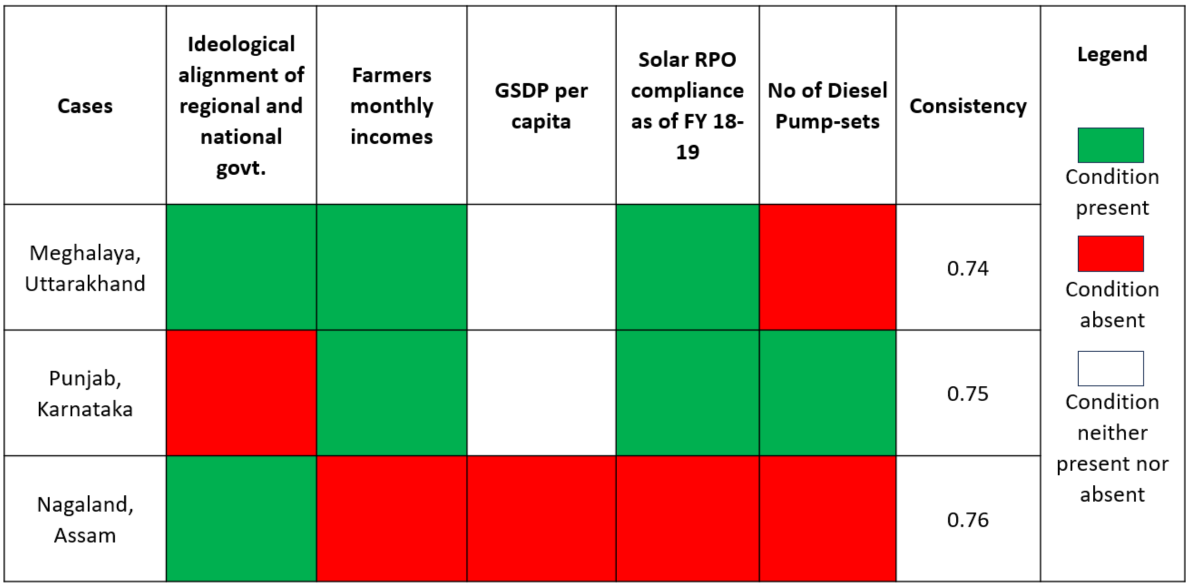

Figure B.10: Solution outcomes of the negative outcomes where the irrigation demand is replaced with number of diesel pump-sets

The results for states with negative outcomes indicate that three of the five states tested under the annual groundwater irrigation draft variable—Meghalaya, Nagaland, and Assam—continue to appear in these solution outcomes. Additionally, new states with similar negative outcomes emerge, including Uttarakhand, Punjab, and Karnataka.

Uttarakhand's outcome resembles that of Meghalaya, with one notable difference: while Meghalaya's financial resources are limited, Uttarakhand is relatively better off financially. In this case, the primary reason for low demand for solar water pumps appears to be the limited presence of diesel pump-sets, which slows down the push for transitioning to solar alternatives.

Nagaland and Assam exhibit negative outcomes similar to those seen when the annual groundwater irrigation draft was tested. Here, the low number of diesel pump-sets diminishes the drive for solar pump adoption, compounded by limited financial resources for both farmers and the state, alongside a lack of policy emphasis on solar energy.

Punjab and Karnataka also display negative outcomes. While both states share some common challenges, their performance in terms of installed pumps varies: Punjab shows moderate progress in pump installations relative to sanctioned targets, while Karnataka's performance is comparatively low. A key factor behind this slower or under-performance in these states appears to be a lack of ideological alignment, as differing policy priorities and objectives have led to inconsistencies in scheme implementation in both Punjab and Karnataka.

C

Appendix C

C.1. Questionnaire for semi structured interview with think tank experts and academia

1. **In your opinion, what are the broader reasons for the disparities in installation quantities in different states under PM KUSUM? How could these disparities be attributed to the factors you mentioned?**

    - **Follow-up:** What do you think would be a major driver in the economic domain that could influence the sanctioned quantities?
        - The relative importance of agriculture in the state, the economic wealth of the state (GSDP), state budgets, etc.?
    - **Follow-up:** Other than economic considerations, could a case be made that the physical requirements drive the demand?
        - Annual irrigation requirements, electricity consumption by the agricultural sector, the number of diesel or electric pump sets that the states intend to replace over the time period of the scheme?
    - **Follow-up:** From a political perspective, in states where the government is not aligned with the national government, does this political difference impact the sanctioned quantities?

2. **The states have a level of autonomy to choose how to implement this scheme. Is there an effect of this autonomy on the variability of sanctioned or installation numbers? How variable are these implementation strategies in general?**

    - **Follow-up:** Some studies suggest that each component of the deployment should be managed by a different implementation body, with the process for availing benefits varying across states. Is this approach more effective or less so?
    - **Follow-up:** Is there a need to standardize these processes? Should successful procedures from certain states be used as a model for implementing agencies in states with fewer successful installations?

3. **Do pilot programs carried out before PM KUSUM, and the knowledge they have developed in the states, provide an advantage to a state in terms of knowledge and process development?**
4. **What broadly could be some other challenges entailed in reaching the de-dieselization target set by the Ministry of New and Renewable Energy?**

C.2. Expert Pool

The expert pool their level of involvement in the policy and their occupational details are shown below:

Praticipant	Type of organization involved	Involvement in policy development	Government consulting about policy	State consulting on policy
Individual 1	Think tank	Yes	Yes	No
Individual 2	Think tank	Yes	No	No
Individual 3	Think tank	Yes	Yes	Yes
Individual 4	Think tank	Yes	No	No
Individual 5	Think tank	No	Yes	No
Individual 6	Think tank	No	Yes	No
Individual 7	Think tank	No	No	Yes
Individual 8	Academia	No	No	No
Individual 9	Think tank	Yes	Yes	Yes

Table C.1: Experts their level of involvement, type of institution they are involved with, and weather they are actively consulting the government on the policy right now

C.3. Implementation in Maharashtra

This section offers a glimpse into the relatively successful implementation of PM KUSUM component B based on conversation with a representative of Maharashtra Energy Development Agency[MEDA]. It offers a context of the implementation processes and some features of implementation. This section though not completely representative of implementation in all states could offer the reader small glimpse into a relatively successful implementation.
The state of Maharashtra stands out as a successful example of implementing PM KUSUM Component B, where both processes and demand have aligned, alongside the deployment of necessary state resources, leading to higher adoption rates. Maharashtra, which has installed the highest number of solar water pumps in India, continues to install more pumps under this scheme. It presents an interesting case of effective state adoption, worthy of further examination. This section outlines key features of the scheme's implementation in Maharashtra and explores potential reasons for the state's relatively successful adoption of solar water pumps. The insights are drawn from a conversation with an individual associated with the Maharashtra Energy Development Agency. While the insights drawn from the conversation with a representative of the Maharashtra Energy Development Agency are not the basis for definitive findings, they serve as a valuable glimpse into a specific instance of relatively successful implementation of Component B of the PM KUSUM scheme, offering contextual understanding to complement the broader analysis.

Figure C.1: Maharashtra Pumps Installed(MNRE, 2019)

The application process for PM KUSUM Component B in Maharashtra is fully online through the MNRE-developed state portal. A nominal fee of Rs. 6 is charged at the time of application to cover administrative costs. The farmer's land records are accessed through an automated system that fetches the required data from the records department. Farmers are also asked to upload their bank details, personal information, and other necessary documentation in the initial application.

Once the application and documentation are submitted, the Maharashtra Energy Development Agency conducts an initial screening based on land ownership size. Farmers with 0.1–2.5 acres of land are eligible for 3 HP solar water pumps, while those with 2.51–5.0 acres qualify for 5 HP pumps. Farmers owning more than 5 acres can access pumps up to 7.5 HP. The farmers owning larger parcels of land also have the option to choose a smaller capacity if preferred.

In addition, data regarding water sources and weather conditions for the farmland are collected. Farmers who have already benefited from the Atal Saur Yojna, or who are connected to the grid through conventional pumps, are deemed ineligible. The eligibility checks are based on records from various agencies involved in providing grid connections. After the initial screening by the central office, a local officer from one of the eight divisional offices cross-checks the submitted documentation with local land ownership records before providing approval. The divisional offices have 4–6 individuals who handle this scheme alongside other projects.

Pumps are distributed on a first-come, first-served basis to ensure fairness. District-wise installation targets are set based on rural population data from the national census, conducted every ten years, a standard program implementation practice in India(Banerjee, 2023). 77.5% of the pumps are available to general category farmers, 13.5% to Scheduled Castes, and 9% to Scheduled Tribes. The state has allocated 60% of the pumps to 3 HP units, 30% to 5 HP, and 10% to 7.5 HP, aligning with the needs of small and marginal farmers.The distribution reflects the smaller average landholding size in Maharashtra compared to states like Punjab and Rajasthan(MoA&FW, 2023).

Once farmers are allotted a pump, they receive an SMS with a payment link. Farmers in the general category must pay 10% of the pump's cost, while Scheduled Caste and Scheduled Tribe farmers pay 5%. In Maharashtra, farmers bear only 5–10% of the total installation cost, with 30% covered by central financial assistance and 60–65% by the state government, depending on the farmer's category. This model is similar to Haryana's, where the state government covers 45% of the installation cost, leaving farmers with only 25% to contribute(Khanna, 2024). A five-year maintenance contract for the pumps is also mandated by the state government. After the payment is made, vendors are selected from the MNRE-approved list.

A second site survey is conducted by the vendor, the local officer from MEDA, and the farmer to confirm the suitability of the land for pump installation. If the site is deemed unsuitable, the application is rejected, and the farmer's initial payment is refunded. If the site is approved, the pump is installed, and the vendor is paid within 15 days post-installation. Vendors are responsible for after-sales service for five years. The government mandates that vendors must install the pump within 120 days of final approval, as recommended by Solar Energy Corporation of India[SECI], an increase from the previous 90-day deadline. This is only after the final approval is made. But in some districts because there are too many applications far exceeding the targets, hence the time for the applications to be addressed is long since its a first come first serve basis installation.

When asked about farmers' responses to Component B, the individual noted that districts like Raigad, Sindhudurg, and Ratnagiri have fewer applications, whereas Beed, Ahmednagar, Nashik, and Jalna report higher demand. Beed, in particular, has the highest demand. Despite this, targets remain fixed based on census data, with no adjustments for districts with higher demand, a standard practice in Indian program implementation. To boost awareness in low-demand districts, MEDA engages in grassroots campaigns, including talks and discussions in village meetings like gram sabhas. MEDA also reaches out to the local agricultural officers at the panchayat samiti or zila parishad level to assist with these awareness campaigns.

Farmers can register complaints about maintenance through the mobile app, website, or at divisional offices. For those without internet access, local krishi seva kendras, aadhar seva kendras, and divisional offices provide assistance with both applications and complaint registration.

In Maharashtra, the state implementing agency's proactive approach has been pivotal in achieving a high installation under PM KUSUM Component B. MEDA has effectively coordinated with the departments of agriculture, water resources, and revenue to not only enhance awareness but also meticulously assess installation sites. The state government has notably extended financial support beyond the mandated 30% to cover up to 60-65% of initial capital costs, demonstrating its deep commitment to the scheme's success. This financial strategy ensures greater accessibility, especially benefiting small and marginal farmers. The distribution of pump capacities—3 HP, 5 HP, and 7.5 HP—carefully considers the specific needs of the beneficiaries, ensuring that the allocations meet the practical demands of the farmers. The implementation process, characterized by settled procedures and a two-stage approval system, ensures fairness and transparency. Additionally, the state's ground-level outreach and systematic complaint addressal mechanisms further illustrate a robust engagement with the farming community, highlighting a comprehensive understanding of the needs of the final beneficiaries. Figure C.2 highlights these reasons for success.

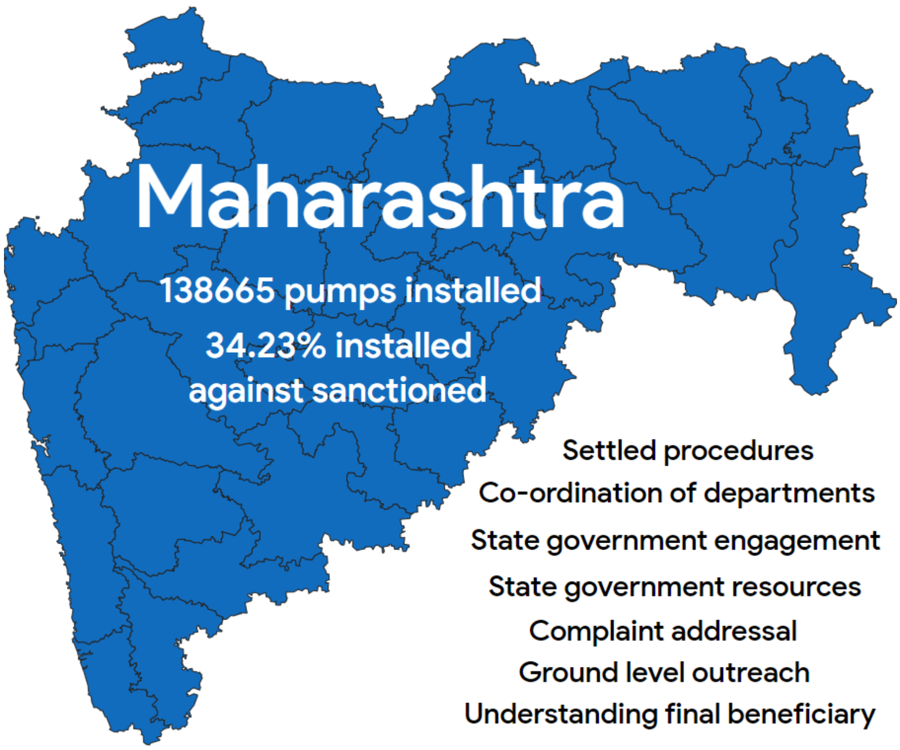

Figure C.2: Maharashtra reasons for successful implementation of PM KUSUM component B(Authors Analysis)