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MASTER'S THESIS

Solar Energy in Indian Agriculture: A Study on the Transition from Fossil Fuels to Sustainable Irrigation

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Candidate number 128

Masters in Climate Change Management

The faculty for engineering and Science/Department of environmental Sciences/Master Climate Change Management

Supervisor: Valeria Jana Schwanitz and August Hubert Wierling

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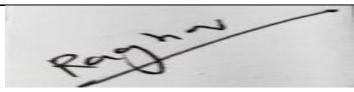
I confirm that the work is self-prepared and that references/source references to all sources used in the work are provided, cf. Regulation relating to academic studies and examinations at the Western Norway University of Applied Sciences (HVL), § 12-1.

Solar Energy in Indian Agriculture: A Study on the Transition from Fossil Fuels to Sustainable Irrigation

Master thesis in Climate Change Management

Author:
Raghav Dwivedi



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This thesis is a part of the master's program in Climate Change Management (Planlegging for klimaendringer) at the Department of Environmental Sciences, Faculty of Engineering and Science at the Western Norway University of Applied Sciences. The author(s) is responsible for the methods used, the results that are presented and the conclusions in the thesis.

Acknowledgement

As I finally conclude my master's thesis on the transition from fossil fuels to solar energy in India's agriculture sector, I'm filled with a sense of achievement and excitement. Examining the details of the complexity of this topic has been a journey filled with challenges, discoveries, and moments of clarity. Exploring how this transition transforms irrigation practices and supports the low carbon energy transition in India has been an eye-opening experience. Unraveling the intricate relationship between fossil fuels, sustainable energy solutions, and the agricultural landscape has deepened my understanding of the urgent need for change in irrigation practices in Indian Agriculture. I am really indebted to my advisors, Valeria Jana Schwanitz and August Hubert Wierling for their unwavering support and guidance throughout my master's program. Their expertise and patience have been invaluable to me and have played a crucial role in the success of this thesis.

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Abstract

Addressing the environmental and economic impacts of groundwater irrigation in India is crucial for a sustainable agricultural future. This study assesses the effects of use of electric and diesel tube wells for irrigation, which are major contributors to carbon emissions due to their high energy consumption in India. Governmental initiatives such as the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme and community-based renewable energy cooperatives like The Solar Pump Irrigators' Cooperate Enterprise (SPICE) in Dhundi village could be pivotal in promoting solar irrigation and helping shift towards renewable fuels. These initiatives offer financial incentives and foster community participation, making solar technology more accessible and supporting sustainable agricultural practices. This study examines the potential of solar-powered irrigation pumps as an alternative, focusing on initiatives like PM-KUSUM scheme and SPICE in Dhundi village, and explores whether synergetic approaches could provide optimal solutions. This research also investigates how the local transition from fossil fuels to solar energy could also contribute to India's pursuit of Sustainable Development Goal 7 (SDG 7) " Ensure access to affordable, reliable, sustainable and modern energy for all".

The study employs qualitative methods, collecting data through semi-structured interviews, later analyzed using a thematic approach and document analysis. The analysis reveals that transitioning to solar pumps can markedly reduce India's carbon footprint, boost crop yields, and enhance farmers' incomes. However, challenges such as high initial costs and the need for technical expertise persist. The research underscores the necessity of coordinated efforts from government bodies, financial institutions, and other stakeholders to overcome these barriers. This investigation highlights the importance of sustained support for renewable energy initiatives to achieve economic and environmental sustainability in India's agricultural sector, thus contributing to the global pursuit of SDG 7.

Samandrag på norsk

Å adressere de miljømessige og økonomiske konsekvensene av grunnvannsvanning i India er avgjørende for en bærekraftig landbruksfremtid. Denne studien vurderer effektene av bruken av elektriske og dieseldrevne borebrønner for vanning, som er store bidragsytere til karbonutslipp på grunn av deres høye energiforbruk i India. Regjeringstiltak som Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM)-ordningen og samfunnsbaserte fornybare energikooperativer som Solar Pump Irrigators' Cooperative Enterprise (SPICE) i Dhundi-landsbyen kan være avgjørende for å fremme solvanning og hjelpe til med å skifte mot fornybare drivstoffer. Disse initiativene tilbyr økonomiske insentiver og fremmer samfunnsdeltakelse, noe som gjør solenergi mer tilgjengelig og støtter bærekraftige landbrukspraksiser. Denne studien undersøker potensialet for solcelledrevne vanningspumper som et alternativ, med fokus på initiativer som PM-KUSUM-ordningen og SPICE i Dhundi-landsbyen, og utforsker om synergistiske tilnærminger kan gi optimale løsninger. Denne forskningen undersøker også hvordan den lokale overgangen fra fossilt brensel til solenergi kan bidra til Indias jakt på bærekraftsmål 7 (SDG 7) "Sikre tilgang til rimelig, pålitelig, bærekraftig og moderne energi for alle".

Studien benytter kvalitative metoder, og samler data gjennom semistrukturerte intervjuer, senere analysert ved bruk av en tematisk tilnærming og dokumentanalyse. Analysen avslører at overgang til solpumper kan redusere Indias karbonavtrykk betydelig, øke avkastningen på avlinger og forbedre bøndenes inntekter. Imidlertid vedvarer utfordringer som høye startkostnader og behov for teknisk ekspertise. Forskningen understreker nødvendigheten av samordnede innsats fra myndigheter, finansinstitusjoner og andre interessenter for å overvinne disse barrierene. Denne undersøkelsen fremhever viktigheten av vedvarende støtte for fornybare energiinitiativer for å oppnå økonomisk og miljømessig bærekraft i Indias landbrukssektor, og dermed bidra til den globale jakten på bærekraftsmål 7.

Western Norway University of Applied Sciences

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Abbreviations

GDP: Gross Domestic Product

GHGs: Greenhouse Gasses

SDG: Sustainable Development Goal

PM-KUSUM: Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan

RECs: Renewable Energy Cooperatives

DSO: Distribution Service Operator

NGO - Non-Governmental Organization

MNRE - Ministry of New and Renewable Energy

IWMI - International Water Management Institute

MGVCL - Madhya Gujarat Vij Company Limited

PPA - Power Purchase Agreement

SPaRC - Solar Power as a Remunerative Crop

1 Introduction

India's economy is experiencing significant growth, and in 2022, its Gross Domestic Product (GDP) reached approximately $3.42 trillion, making it the fifth-largest economy in the world. This highlights India's substantial economic expansion, driven by a large population, increasing industrial output, and a burgeoning services sector (*World Bank Open Data*, n.d.). This is supported by India's economy being significantly bolstered by its agricultural sector, which employs around 58% of the population and contributes 17% to the nation's GDP (Wagh & Dongre, 2016). Over 70% of Indian agriculture relies on irrigation, heavily depending on groundwater resources. In the realm of electrical energy, the agricultural sector commands a significant share, primarily driven by the necessity of powering irrigation pumps. This heavy reliance underscores the critical need for a dependable and sustainable power infrastructure. However, the prevalent issues of poor quality and unreliable power supply in India compel farmers to resort to fossil fuels, particularly diesel, for their irrigation needs. This dependence not only adversely affects the environment by contributing to the emission of greenhouse gases (GHGs) but also negatively impacts the profitability of farmers (Gautam et al., 2020). Such emissions play a pivotal role in exacerbating climate change, thereby impeding the global objective of attaining United Nations Sustainable Development Goal (SDG) 7, which aims to ensure access to affordable and clean energy for all (World Bank Group, 2022).

In view of expected economic growth in the agriculture sector, it is therefore important to enable a low carbon energy consumption pathway. This means ramping up renewable capacities, switching from fossil to renewable fuels, and increasing energy efficiency in the agriculture sector. At the same time, energy supply needs to be reliable and affordable, aligning with SDG7 "Affordable and Clean Energy". Transitioning to renewable energy sources like solar power for irrigation can address these challenges, reduce greenhouse gas emissions, and support sustainable agricultural practices. Although India has reached grid parity for solar power, the right model of commercialization has not yet been established in the agriculture sector. Technological innovation offers emerging countries the opportunity to leapfrog the traditional energy system. However, in India, development is restricted by various barriers, including economic, social, and infrastructural barriers. Overcoming these barriers is crucial to increasing the deployment of renewable energy. India, with its high solar, wind, and biomass potential, stands to benefit significantly from such transitions (*World Bank Open Data*, n.d.-b).

By adopting sustainable energy practices, India can enhance agricultural productivity, reduce environmental impact, and support its economic growth. This study explores how government initiatives like the Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan(PM-KUSUM) Scheme and Renewable Energy Cooperatives (RECs) can facilitate this energy transition in India's agricultural sector. In addition to the government initiative. In India, decentralized energy is an option to expand the electric network to remote locations inaccessible by the grid. In this way, the achievement of SDG 7, namely the provision of access to electricity for all, can be supported.

Taking these views as a departure point, the objective of the study is to investigate in the case of India how innovative forms of irrigation through government initiatives like PM- KUSUM and RECs can help overcome barriers in developing countries, supporting the SDG 7. To answer the above research question, a case study on the Dhundi Energy Cooperative is carried out, examining the synergy between government policies like PM-KUSUM and RECs like Dhundi Energy Cooperative.

The main research question is:

How does the transition from fossil fuels to solar energy transform the irrigation practices within India's agriculture sector and how does it support pursuing the low carbon energy transition in the country?

The sub-research questions are:

1. How has the dependence on fossil fuels impacted the performance of SDG7 affordable and clean energy for irrigation practices in India?

2. What is the role of the government in the transition from fossil fuel-based to solar energy renewable systems?

3. Can energy cooperatives support the transition from fossil fuel-based to solar irrigation systems?

The remainder of the study is structured as follows:

Chapter 2: Provides an overview of current irrigation practices in India and their relevance for SDG 7 through government initiatives and existing renewable energy cooperatives. This leads to the identification of research gaps.

Chapter 3: Describes the research design and methods, which are qualitative case study methods.

Chapter 4: Describes the conclusion, findings and recommendation to future readers derived from the case study and interviews.

2 Literature review

2.1 The Challenges of Irrigation in Rural India

In rural India where access to electricity is frequently unreliable, farmers resort to diesel pumps for irrigation purposes (Shah, 2009b). However, because diesel emits carbon dioxide (CO_2) and other greenhouse gases during operation, using it increases production costs and poses environmental risks (Gautam et al., 2020). In the past, about 31 million hectares have been irrigated using electric tubewells, resulting in the release of 11.09 million metric tons of CO_2. This accounted for 77% of all emissions from deep groundwater irrigation. Additionally, about a quarter of all emissions came from diesel tubewells, which irrigated 4.1 million hectares and emitted 3.29 million metric tons of CO_2. Overall, groundwater irrigation led to the emission of 14.38 million metric tons of CO_2, covering approximately 35.1 million hectares (Tripathi et al., 2016).

The heavy reliance on fossil fuels for irrigation in rural India poses obstacles to achieving SDG 7, which aims for affordable and clean energy for all (Lup et al., 2023). Understanding India's energy sector is crucial for sustainability, especially its impact on irrigation. Over 70% of rural households in India, the country with the largest economy in South Asia, rely mostly on agriculture for their income (Gautam, 2020). India's agricultural sector is ingrained in the country's social fabric and has a long history. It accounts for over 58% of job possibilities in the country and contributes approximately 17% of GDP (Wagh & Dongre, 2016). Along with a wide range of fruits and vegetables, the nation grows significant crops such rice, wheat, sugarcane, cotton, pulses, and oilseeds (Kannan, 2011). By creating foreign exchange profits and sustaining the livelihoods of millions of people involved in the agricultural value chain, the export of these agricultural products greatly boosts India's economy (Gautam, 2020). The Southwest monsoon, which runs from June to September and has erratic patterns all over the nation, is a major contributor to India's agricultural production (Rakshit et al., 2024). In India, there is no other option for irrigation due to the unpredictable nature of monsoon rainfall and its unequal distribution. Farmers cannot rely only on rainfall; they also need pump irrigation. Hence, groundwater supplies are crucial to the farming industry (T. Shah, 2009). This poses a huge challenge to rural farming as many households and farms lack access to electricity as high voltage power is required to operate the irrigation pumps (*Sustainable Development Report 2023*, n.d.). Moreover, it is also expected that the problem is even growing in the future due to expected impacts of global warming on weather patterns (*How The Climate Crisis Is Impacting India*, 2022).

In India, providing electricity for groundwater irrigation is more than just installing meters and power lines; it's a matter of millions of farmers' livelihoods and the survival of rural villages. Gulati and Pahuja In their article, they also mentioned that to address challenges in electricity generation, farmers have been provided with free or heavily subsidized power for decades. While this support has been essential, it has also led to some unexpected consequences. Farmers deal with an unstable power supply and depleting groundwater supplies while electricity distribution companies (i.e., distribution service operators, DSOs) are grappling with financial losses and infrastructure issues. Everyone is impacted by this intricate network of problems, ranging from field farmers to the DSOs. The choices made in the 1970s to move from metered to flat-tariff power pricing looked reasonable at that time, but they also started a series of events that have resulted in the difficulties farmers have today. Farmers nowadays face a difficult situation since they must rely on free electricity, yet its quality and consistency is unstable. DSOs, meanwhile, struggle to keep running in the face of declining infrastructure and financial shortfalls (Gulati & Pahuja, 2015). The government scheme to subsidize the farmers such as Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme's impact on recipients, such as changes in cropping patterns, debt levels, and water usage, remains unexamined. While agencies monitor its progress, farmer feedback is crucial to assess its real-world effects. States are updating databases to accommodate ongoing PM KUSUM initiatives. While past solarization projects were tracked quantitatively, understanding PM KUSUM's full impact requires qualitative analysis to gauge socio economic changes in farming communities. Issues such as inconsistent power supply and voltage fluctuations in tubewell irrigation systems result in higher maintenance costs, affecting efficiency and uniform water distribution (Dutt & Krishnan, 2023).

2.2 Current Deployment of Solar-Powered Irrigation

Many studies suggest that the use of solar power for irrigation can help solve the problem of rural irrigation when access to electricity is limited or lacking. In 2015, India had 5.36% of its electricity capacity coming from renewable sources, excluding hydroelectric. This category includes geothermal, solar, tides, wind, biomass, and biofuels. By 2019, the annual additions of renewable power capacity had increased substantially. By 2040, with a concerted focus on expanding solar and wind power, this percentage could rise significantly, reflecting the trend of increasing reliance on renewable energy sources, especially in regions with limited access to electricity. Despite progress, much potential remains untapped. As of recent reports, approximately 350,000 diesel pumps have been replaced by solar-powered alternatives in India. This transition is part of a broader initiative under the PM-KUSUM scheme, which aims to solarize agricultural pump sets to reduce dependence on grid electricity and diesel, thereby promoting sustainable farming practices and reducing carbon emissions indicating a positive trend (*Solar Water Pumps Redefining Farmers' Lives*, 2022). However, this figure falls short of the considerable potential for adoption.

Studies highlight several barriers hindering the realization of this potential. Notably, achieving a balance between economic growth and environmental preservation necessitates comprehensive planning and policy interventions (Rudnick et al., 2022). Research by Sedai et al. (2021) underscores how insufficient energy access exacerbates socio-economic disparities, particularly affecting marginalized communities. Transitioning to sustainable energy faces obstacles like high costs, social barriers, poor infrastructure, and limited knowledge. To overcome these challenges, policymakers must prioritize community needs. Initiatives such as capacity-building projects and renewable energy subsidies can facilitate rural development, offering practical solutions for reconciling environmental sustainability with economic progress (Sedai et al., 2021). Additionally, improving the quality of demand forecasting is essential from a technical standpoint to ensure effective implementation.

The figure 1 represents the renewable energy production data from 2013 to 2019 across four categories: solar wind power, wind power, hydropower, and a combined category including bio power, geothermal, ocean power, and CSP wind thermal. Solar wind power exhibits remarkable growth, increasing steadily from 37 units in 2013 to 115 units in 2019 (Dey et al., 2022).

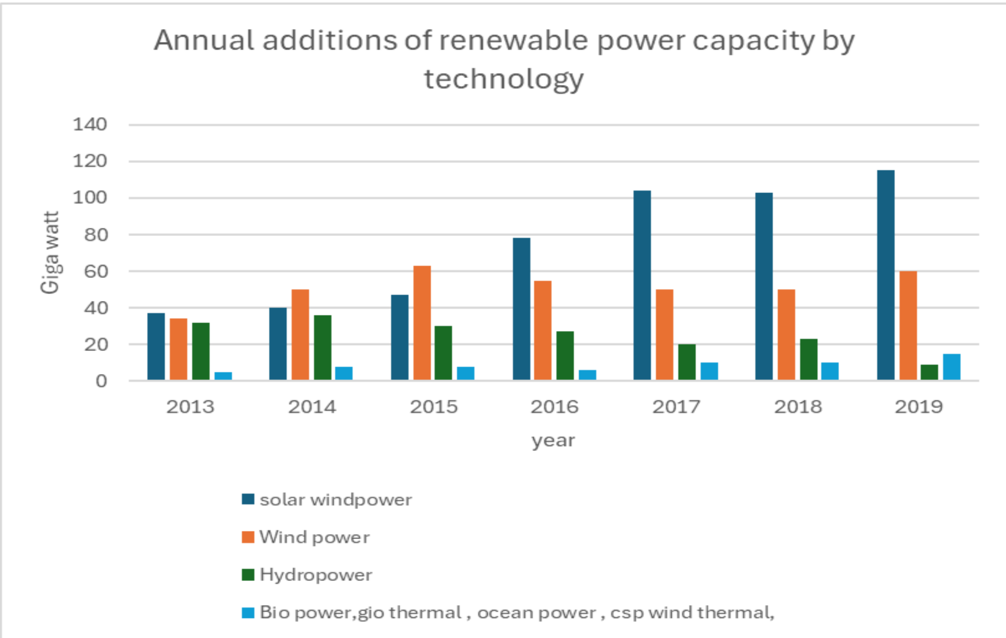

Figure 1 Annual Additions of renewable power capacity, by technology and total, 2013- 2019 Source figure 1 (Dey et al., 2022)

2.3 Current Policy and Planning Support for Improving Low Carbon Rural Irrigation in India

Figure 2 Empowering Agriculture: Kusum Yojana's Solar Initiative, Source (Solar, 2023)

India has several programs in place to support rural irrigation. PM KUSUM, a government program designed to increase farmers' income and encourage sustainable farming methods, has the potential to be a viable alternative to the established dependency on fossil fuels, especially diesel, for farming operations .Scholars highlight that The PM KUSUM Yojana stands out because it provides a focal point for investigating ways to lessen the negative environmental effects of using fossil fuels in agriculture (Sarkar et al., 2023b).

The PM KUSUM Yojana program provides a means of cutting carbon emissions and lessening the environmental impact of using traditional energy sources by providing incentives for the installation of solar pumps and decentralized solar power plants. In March 2019, the PM KUSUM plan received administrative clearance, and in July 2019, guidelines were established. The Ministry of New and Renewable Energy (MNRE) introduced the program to install solar pumps and other new power plants throughout the nation where it was decided to provide a 60% subsidy for the installation of tube wells and pump sets to each farmer. Additionally, the government will loan them 30% of the entire cost. By 2022, the project hopes to install 25,750 MW of additional solar and other renewable power. The total federal financial support, including service fees to the implementing agencies, is Rs. 344,220 million.(Sarkar et al., 2023).

There are three major parts to the PM-KUSUM concept. First, Component A entails establishing dispersed grid-connected solar or other renewable energy-based power plants that are positioned on stilts or the ground. In places without grid supply, Component B's second main objective is to install standalone solar pumps in lieu of diesel irrigation pumps. The solarization of grid-connected agricultural pumps is the final goal of Component C, whose solar photovoltaic (PV) capacity is double that of the pump capacity. This extensive plan contributes to India's sustainable energy goals by addressing a variety of renewable energy adoption issues, from direct replacement of traditional diesel pumps to decentralized power generation (Sarkar et al., 2023a).

The development of PM KUSUM programs is being actively watched by agencies, however assessing its practical effects in the field depends heavily on farmer input. To assist the ongoing PM KUSUM efforts, states are currently updating their databases. In contrast to earlier solarization initiatives, which were mostly assessed numerically, understanding the full impact of PM KUSUM requires qualitative study to evaluate the socioeconomic changes that occur within farming communities.

2.4 The Potential for Renewable Energy Cooperatives

Renewable Energy Cooperatives (RECs) are discussed as a means to foster reducing carbon emissions and contributing to rural electrification. They build on business models in which members of a community come together to jointly own and manage renewable energy and enable energy-savings. Open membership, democratic decision-making, and environmental conservation are among the ideals upheld by these cooperatives (Cooperative Identity, Values & Principles ICA, 2024). Because everyone is participating, RECs are a good way for the community and the environment compared to centralized ownership, where a few people manage everything (Schwanitz et al., 2023).

The concept of cooperatives in India has been firmly established, with significant engagement in the energy sector. Over 800,000 cooperatives operate in the country, spanning various sectors (National cooperative union of India , n.d.) Notably, the government has been actively promoting renewable energy cooperatives to advance rural electrification and sustainable energy practices, with projects including solar power and biogas initiatives (Ministry of New and Renewable Energy | India, n.d.). Recent data indicates a rise in renewable energy cooperatives focusing on solar, wind, and biomass projects. In rural India, agricultural cooperatives are highly prevalent, numbering over 150,000. They play pivotal roles in supporting farmers by collectively managing resources, procuring inputs, and marketing produce. Often serving as a model for energy cooperatives, these agricultural cooperatives leverage their community networks and organizational expertise to facilitate the adoption of renewable energy technologies at the grassroots level (Ministry of Rural Development | Government of India, n.d.).

REC projects have seen success and popularity in Europe (Lowitzsch et al., 2020), yet India has been slow to initiate similar endeavors in the energy cooperation sphere (Jain & Rossow, 2023). While some cooperative ventures have faced setbacks, one cooperative has been successful in its initiative which is known by the Dhundi cooperative (Kottantharayil et al., 2020). Hence this study conducts interviews with both parties as part of a case study. The objective is to explore the case and find answers to the practical challenges and opportunities for shifting from fossil fuels to solar energy in India's agriculture sector.

3 Methodology

3.1 Reflections on the General Research Approach

This thesis uses qualitative design and methodology, drawing upon the ideas of several authors. Hence, I capture a diverse range of viewpoints (Palmer & Bolderston, 2006). I follow the idea of Guerreiro that study design is about discovering, characterizing, understanding, and forecasting the nuances of human experience—not merely checking boxes (Guerreiro, 2017). Furthermore, Rahman (2016) elaborates on the fact that qualitative research is about exploring the lives, emotions, and interactions of actual people rather than being limited to lab settings. These viewpoints served me as a helpful reminder that each research participant contributes with a distinct narrative to my study, broadening my perspective on the world (Rahman, 2016). To expand my respondent pool, I utilized a referral sampling technique, where initial contacts referred me to other relevant stakeholders and experts within the field of irrigation and energy sector in India (Leighton et al., 2021).

3.2. Case Study Design

The thesis carries out a case study to answer the question how energy cooperatives can support the introduction of solar-based irrigation in rural India. A case study produces a comprehensive, multifaceted understanding of a complicated problem in its actual setting. It is a well-known research method that is widely applied across many fields (Crowe et al., 2011). As the author Ridder explains, a case study helps with the bigger picture by identifying similar pieces of information to connect other events. It also helps to gather more diverse perspectives by broadening the sample of interested parties. The cases are those selected within the energy cooperative sector industry in consultation with their interested parties, as previously discussed. For each case, the units of analysis are the different stakeholders (Ridder, 2017). The strength of this research method is also its ability to discover a wide variety of social, cultural, and political factors potentially related to the phenomenon of interest that may not be known in advance. Analysis tends to be qualitative in nature, but heavily contextualized and nuanced (Pelz, n.d.).

In alignment with my research interests and objectives, I adopted a purposive sampling approach (Campbell et al., 2020) to ensure that the selected case studies reflect the complexity and diversity of irrigation practices in India. It meant selecting cases that address the specific research question, also resonating with my personal experiences and aspirations as a researcher. The study primarily concentrated its search on renewable energy projects in rural India that include both successful and unsuccessful renewable energy projects in rural India. By encompassing a diverse range of projects, the study aims to provide a comprehensive understanding of the challenges and opportunities associated with renewable energy initiatives in the region. This decision aimed to foster open discussions and exchange viewpoints on ongoing developments without being constrained by predetermined outcomes. By prioritizing projects in development, the study sought to explore decision-making processes and challenges faced by stakeholders. This approach aimed for a flexible and organic research process, capturing the complexities of rural renewable energy initiatives.

Moreover, my deliberate choice to prioritize case studies where I had access to firsthand information or could establish connections with key stakeholders easily underscored my commitment to conducting contextually relevant and impactful research. I conducted a search for renewable energy projects in India focused on transitioning from fossil fuels to solar energy, specifically targeting improvements in irrigation practices within the agricultural sector. These projects were selected to support the broader goal of enhancing renewable energy technology deployment. A list and map of projects and their location is shown in Table1. I established criteria to guide project selection, which are summarized in Table 1.

Project	Criteria for choosing projects
PM KUSUM YOJANA	• Situated in rural areas where electricity and sustainable irrigation practices are essential. • Involvement of government initiatives. • Demonstrates success or progress in overcoming barriers to renewable energy deployment. • Offers opportunity for in depth case study analysis • Access to firsthand information or connections with key stakeholders • Addresses the specific research question and aligns with personal experiences and aspirations of the researcher.
Dhundi Solar Pump Irrigator`s Cooperative Enterprise SPICE	• Situated in rural areas where reliable electricity and sustainable irrigation practices are essential. • Involvement of government initiatives like RECs. • Demonstrates success or progress in overcoming barriers to renewable energy deployment. • Offers opportunities for in-depth case study analysis. • Access to firsthand information or connections with key stakeholders. • Addresses the specific research

	question and aligns with personal experiences and aspirations of the researcher.

Table 1: List of Projects and criteria for choosing the Projects.

Projects situated in rural areas where reliable electricity and sustainable irrigation practices were essential conditions for selecting the criteria. I focused on projects involving government initiatives like PM-KUSUM and RECs, aligning with my study's emphasis on innovative governance and collaboration. Projects demonstrating success or progress in overcoming barriers to renewable energy deployment. Projects offering opportunities for in-depth case study analysis to explore the roles of government schemes and energy cooperatives in facilitating the transition to solar energy for irrigation. I conducted initial research to gather information about potential projects meeting the selection criteria. This involved preliminarily reviewing documentation of the projects, reports, and relevant literature to assess their suitability for my study.

Based on my preliminary evaluation, I narrowed down the list of potential projects to those aligning best with the selection criteria and offering the greatest potential to contribute to achieving my research objectives. Finally, I selected one or more projects from the narrowed-down list that provided the most promising opportunities for investigation. These projects are closely aligned with my study's focus on understanding the transition from fossil fuels to solar energy for irrigation in India's agricultural sector. Figure shows the geographical location of the case study of the cooperative that we chose for conducting the case study, i.e. the Dhundi renewable cooperative.

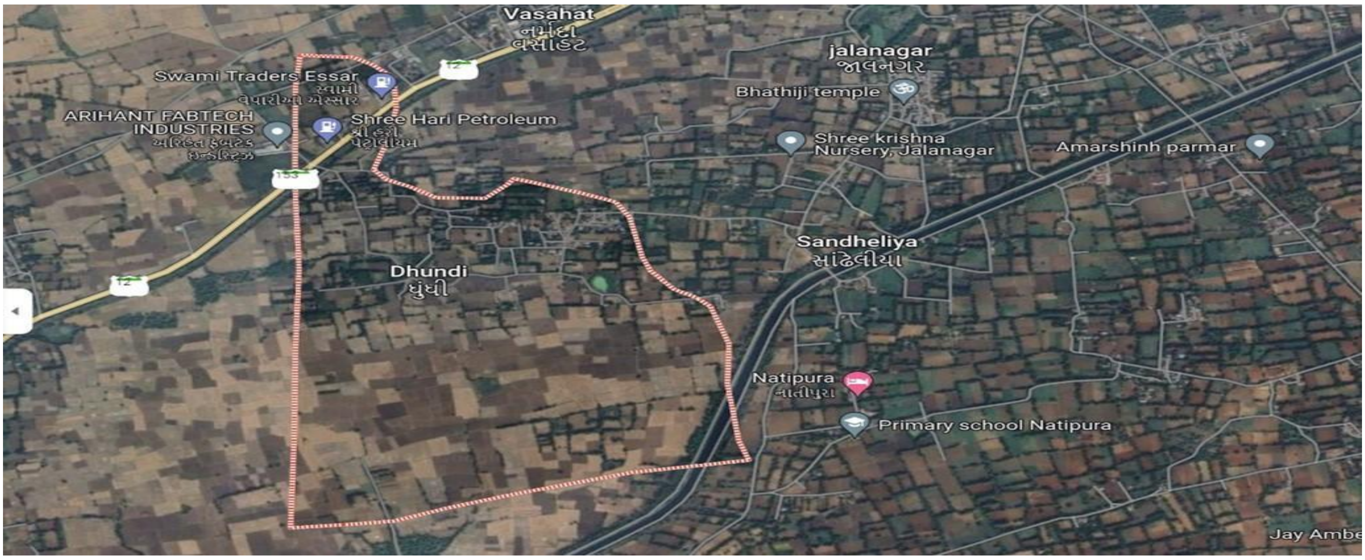

Figure 3: geographical location of the case study Source : Google Map

I employed a purposive sampling strategy to identify potential respondents for my study. The statistical procedure known as "sampling" involves choosing a subset, or "sample," of an interest so that observations and statistical conclusions can be drawn about the population. To enable the conclusions drawn from the sample to be applied to the population of interest, it is crucial to select a sample that is accurately representative of the population (Pelz, n.d.-b). By leveraging my existing network and rapport with stakeholders, I got access to key informants and decision-makers in the field of irrigation and energy sector in India, thereby enriching the depth and breadth of my data collection efforts. To expand my respondent pool, I utilized a referral sampling technique, where initial contacts referred me to other relevant stakeholders and experts within the field of irrigation and energy sector in India. This approach allowed for the identification of additional participants who may not have been initially included in my network, thus broadening the scope of insights gathered for my research. Recognizing the value of diverse perspectives and lived experiences, I sought to engage stakeholders from various stakeholder groups, ensuring a wide distribution of perspectives and minimizing biases in my research. Through careful consideration of sampling criteria and proactive outreach efforts, I endeavored to capture the complexity and nuances of stakeholder dynamics, ultimately contributing to a more comprehensive understanding of the issues at hand.

Interviewee Category	Who were interviewed	Number of contacts
Individual farmers from various communities	Individual farmers from various communities	10
Energy cooperatives members	Members of energy cooperative i.e. Dhundi cooperatives	5
NGOs executives	Local and regional NGOS officials involved in PM KUSUM and other initiatives	5

Table 2: No of interviewees and category of interviewees

I carried out semi-structured interviews, which were done virtually to hear from people in the energy sector. By asking the right questions and really listening, these interviews aimed to understand the different perspectives on the energy sector. Interview data were complemented by data obtained from document analysis. By exploring various digital sources like articles and reports from trusted online sources, I gained valuable extra perspectives on the energy sector in India. As I proceeded from collecting data to analyzing it, I blended two methods. Thematic coding revealed patterns in what stakeholders said about energy deficit in rural India, while content analysis dug deep into digital documents for key points. Together, these methods gave me a clear picture of stakeholders' views. Bringing together these two methods, I developed a clear view of what stakeholders think about the energy consumption in irrigation practice in India. I carefully compared and combined the data to understand the details, find similarities, and spot differences in their views. By doing this, I aimed to make sense of the complex topic of energy consumption in irrigation and offer practical ideas for policymakers and industry professionals.

For a detailed explanation of the coding used in my analysis and the rationale behind it, please refer to Appendix C: Coding Documentation. This appendix provides a comprehensive overview of the coding methodology, including the specific codes utilized for variables and the rationale behind their selection.

A variety of diverse, primarily qualitative methodologies are used in the research field of discourse analysis to examine the connections between language use and society. Most language researchers see language as a social practice that shapes the social environment and vice versa (Giotitsas et al., 2022). Among them one is discourse analysis provides a lens through which I can view the many functions of language. This includes shaping prevailing power structures, constructing societal narratives, influencing our everyday dialogues, molding opinions, and more (Politz, 2024). Hence in delineating the methodological pathway for data analysis in my study, I underscore a dual emphasis on discourse and content analysis. Recognizing the invaluable insights afforded by discourse analysis, my research revolves around unraveling the discourses and narratives embedded within the qualitative data. Discourse analysis serves as the primary lens through which I explore the diverse perspectives, ideologies, and power dynamics articulated by the participants.

The journey of data management initiates with the meticulous transcription of interview recordings, aiming to faithfully capture the participants' voices while eliminating any superfluous elements. These transcripts serve as the cornerstone for discourse exploration, encapsulating the essence of the participants' discussions in their authentic expressions. Leveraging discourse analysis tools, I delve into the intricacies of these discourses, discerning underlying themes, ideologies, and rhetorical strategies that encapsulate the essence of the participants' viewpoints.

Along with discourse analysis, I embrace a content analysis approach to uncover broader patterns and trends within the data. Content analysis offers a systematic framework for organizing and interpreting the myriad discourses uncovered. Drawing on established frameworks and theoretical concepts, I identify recurring themes and motifs that traverse across the discourses, shedding light on the collective experiences and perspectives of the participants.

The coding scheme employed in the analysis is informed by both discourse and content considerations, facilitating a comprehensive exploration of the data. Themes are identified based on overarching concepts and ideas emerging from the discourses, while also aligning with the broader research questions and objectives. This integrated approach ensures a nuanced understanding of the research topic, grounded in the lived experiences and voices of the participants.

In summary, my data analysis approach combines the rhetorical richness of individual discourses with systematic exploration of broader themes and patterns. Through this synthesis of discourse and content analysis, I endeavor to unveil the multifaceted dimensions of the research topic, offering insights that resonate with the complexity of human discourse. See the table for detailed understanding of the coding process, people interviewed , interview questions and transcript from the notes.

Appendices	Content
Appendix A	Coding documentation, Detailed explanation of the coding used in the analysis including specific codes utilized for variables and the rationale behind their selection.
Appendix B	List of interviewed people and their characteristics. Table listing interviewed individuals, their roles and key characteristics
Appendix C	Interview Questions, List of questions used in semi structured interviews.

Table 3: List of Appendices

3.3 Ethical Considerations

Ethical guidelines in participant observation research emphasize avoiding harm to communities and individuals that includes asking for their consent,and ensuring confidentiality. Overt research involves disclosing one's presence and objectives to the group or community being studied. Covert research is generally considered unethical (Wilson, 2005).

Initiating a scholarly investigation necessitates a firm grasp of academic research language and ethical standards. Upholding participant safety and well-being, along with observing ethical guidelines and professional conduct, are indispensable for upholding the credibility and reliability of the research findings (Cacciattolo, 2015). I have reflected upon this and understood the potential limitation of my own biases. During my research, I have taken time to contemplate the significance of my work. Apart from addressing the agricultural energy sector in India, It is a study that links energy research to society. Numerous factors impact energy demand in the agricultural sector, there are millions of perspectives to consider. I am grateful for the respondents' trust in me, and I take my role seriously. I ensured that I followed the guidelines for research ethics in the social sciences. Following this I ensured that all informants were informed about the society and gave their informed consent before conducting the interview. They were informed about the type of study, how they would be referred to in the research and how they could access their data; see appendix for consent form.

3.4 Limitations

The limitations outlined here serve to provide insight into the interpretation of the findings and suggest avenues for future research, as discussed in the concluding chapter. In this case study, I interacted with respondents virtually to collect data. Conducting research virtually, as in my case when I was researching in Norway, poses several limitations. These include challenges in building rapport with participants and a potentially limited understanding of the research context due to the absence of physical presence and restricted access to resources, which may impact the depth and quality of the findings. Having embarked on my research journey, I also encountered hurdles in accessing crucial data or resources essential for a comprehensive study. These obstacles stemmed from constraints in both time and budget. Despite my best efforts, the limited time available made it challenging to thoroughly explore all avenues and gather the necessary information. Similarly, budgetary limitations constrained my ability to procure access to certain datasets, documents, or specialized tools that could have enriched my research. As a result of these constraints, the depth of my investigation was inevitably compromised, limiting the breadth of sources I could tap into and thereby impacting the robustness of my findings. I found myself grappling with the realization that certain aspects of the research remained beyond my reach due to these limitations. Despite the frustration, I remained committed to making the most of the resources available to me, striving to overcome these challenges and produce meaningful insights within the constraints I faced. This experience underscored the importance of resource management and strategic planning in research endeavors, highlighting the need for flexibility and adaptability in navigating unforeseen obstacles. Furthermore, I also recognized the potential for subjectivity in the findings, given the diverse perspectives of stakeholders involved. This subjectivity could introduce variability in the results, as each stakeholder's viewpoint reflected their own biases and interpretations.

4 Presentation and Discussion of Results

This chapter presents the findings of the research based on data collected through interviews and case studies. The primary objective is to evaluate the implementation and impact of government initiatives like PM-KUSUM, as well as the role of RECs, in promoting sustainable irrigation practices in India. These initiatives aim to mitigate climate change by supporting SDG7, which pertains to affordable and clean energy. The study also attempts to present the practical challenges and opportunities of shifting from fossil fuels to solar energy in India through the firsthand information provided by the farmers and members of NGOs and RECs The results are structured around the research questions outlined in Chapter 1.

4.1 Results

Data was collected through semi-structured interviews with stakeholders including the NGO executives responsible for PM-KUSUM scheme and Dhundi Solar Cooperative, farmers who benefited from the PM-KUSUM scheme and the members of the Dhundi Solar Pump Irrigators' Cooperative Enterprise (SPICE). Additionally, secondary data from relevant reports and publications were analyzed.

4.1.1 Transition from Fossil Fuel-based Irrigation to Solar Energy

The research uncovered various ways farmers in rural areas water their crops. They use everything from old-fashioned canals to modern pumps powered by diesel or electricity. But even though efforts have been made to bring electricity to these areas, most of it is used for homes rather than farms. This means farmers often struggle to get enough electricity for their irrigation needs because the supply is unreliable, with frequent power cuts and voltage problems.

Adding to the problem is that electricity can be expensive, and farmers sometimes find it hard to pay their bills. This puts more pressure on the companies that provide electricity. All of this shows that there's a complicated relationship between providing electricity and making sure it helps both homes and farms.

On top of dealing with electricity issues, farmers also have to cope with less water in the ground and fewer natural water sources like ponds. This makes it harder for them to grow crops consistently. So, they're looking for new ways to water their crops, and many still rely on diesel pumps despite their high costs and environmental impact. Using diesel pumps means spending a lot on fuel and keeping the engines running smoothly, which can be tough for farmers who don't have much money. And while diesel pumps aren't great for the environment, they're still a lifeline for many farmers who need a reliable way to water their crops.

Local Farmer 1: "Electrification has been done in our area but the major issue is reliability, quality and affordability of electricity. Power for irrigation is supplied at late night and we have to do irrigation at late night which is risky because of the risk of snake and scorpion bites."

Local Farmer 2: "Since the electricity we are getting is unreliable (only for 7-8 hours), poor quality (as the voltage is extremely low and not sufficient to run the irrigation pump) and expensive so we don`t feel the need to pay for the electricity bill if it doesn't serve our purpose of irrigation."

Local Farmer 3: "Groundwater levels have really dropped, and since we're so dependent on it for irrigation, it's creating big challenges for us. Many of our ponds and other water sources have dried up, making things even harder, having used the used diesel-powered systems has helped solve this problem but the diesel motors incur huge noises and operation costs."

Local Farmer 4: "We used diesel pumps which were costly and needed constant refueling. When we use a diesel pump for irrigation, we also need one more person to operate on it and also have to pay him also."

Local Farmer 5: "When fuel prices rise sharply or fluctuate unpredictably, it leads to increased operational costs. Paying a hefty amount of money for the diesel is like burning my own blood and these fuel prices ate most of my profit"- Local farmers in Dhundi community.

Local Farmer 6: "We know diesel is bad, but right now, we don't have another option."

NGO Executive 1: "Diesel-powered systems have contributed to adverse environmental impacts, further exacerbating issues such as greenhouse gas emissions and air pollution."

NGO Executive 2 : "Moreover, using fossil fuels has made it harder to switch to renewable energy. Farmers who have already invested in diesel infrastructure are reluctant to adopt solar technology, despite its long-term benefits. This reluctance can delay the widespread adoption of clean energy solutions, thereby impeding progress towards achieving SDG 7 targets. The transition to renewable energy sources like solar pumps is crucial for reducing carbon emissions and promoting environmental sustainability in the agricultural sector."

Diesel-powered systems also have contributed to negative environmental impacts, exacerbating issues such as greenhouse gas emissions and air pollution. In many places the farmers are well aware of the negative effects, but they believe there are no better alternatives. Some farmers are aware of the alternatives while some are still seeking alternatives. The burning of diesel fuel releases greenhouse gasses like CO_2 and other pollutants into the atmosphere, contributing to climate change and posing health risks to both humans and ecosystems. The combination of high operational costs and adverse environmental effects added economic pressure on farmers, making it difficult for them to maintain profitability while also contributing to environmental degradation. Secondly, reliance on imported fossil fuels creates energy security issues. Fuel supply disruptions, whether due to geopolitical tensions, natural disasters, or logistical problems, can affect the availability of energy for irrigation. This dependency on external sources of energy limits the ability of farmers to control their energy supply, making them vulnerable to external shocks and disruptions. This lack of energy security can severely impact

the regularity and reliability of irrigation, which is crucial for consistent agricultural production. This situation has created a pressing need for alternative irrigation solutions that could alleviate these challenges. The transition to solar pumps has addressed many of these concerns. Solar-
powered irrigation systems harness energy from the sun, providing a renewable and environmentally friendly source of power.

4.1.2 Role of Government in Transition from Fossil Fuels to Solar Energy in the Irrigation System

The second research question investigates the role of government initiatives, particularly PM-KUSUM, in facilitating the transition from fossil fuel-based to solar energy systems.

PM-KUSUM Beneficiary Farmer: "Initially, I didn't know about this government policy. Additionally, there were some middlemen charging a fee for the application process. However, I later discovered that I could apply online."

PM-KUSUM Beneficiary Farmer: "The team members of an NGO who led the initial workshop approached me and explained the subsidy process."

PM-KUSUM Beneficiary Farmer: "We received a subsidy which covered a large part of the installation costs."

PM-KUSUM NGO Executive: "The experience of solar irrigation models in the villages have been excellent, and he appeals to the government to bring this further into consideration."

PM-KUSUM NGO Executive: "At the heart of the PM KUSUM Scheme lies its inclusivity, welcoming various entities such as individual farmers, farmer groups, producer organizations, panchayats, cooperatives, and water user associations. This approach ensures that a diverse range of stakeholders can access the scheme's benefits, fostering sustainable agricultural development. However, despite its promising outlook, the PM-KUSUM Scheme encounters several hurdles, notably the high upfront costs of solar infrastructure, limited access to affordable credit, and the demand for technical expertise in *maintenance. Overcoming these obstacles necessitates collaborative efforts from government bodies, financial institutions, and stakeholders to ensure the scheme's effective implementation and scalability."*

The PM-KUSUM Scheme, launched by the Government of India in March 2019, represents a significant effort to transition farmers to solar energy for irrigation. This scheme, overseen by the MNRE, aims to reduce greenhouse gas emissions, enhance the income of Indian farmers while promoting sustainable agriculture practices. Under PM KUSUM, farmers receive substantial financial support to install solar irrigation pumps, thereby reducing their dependence on diesel-powered pumps. PM-KUSUM is a policy implemented by the government of India in which solar pumps are being installed in farmer's places and subsidies are also provided. One of the primary objectives of the PM KUSUM Scheme is to provide farmers with access to cutting-edge technology for irrigation while reducing reliance on diesel and promoting cleaner energy sources. By subsidizing the installation of solar pumps, the scheme facilitates more effective and environmentally friendly irrigation practices.

Solar pumps harness renewable energy from the sun, offering a reliable and sustainable alternative to diesel-powered pumps. This transition reduces operational costs for farmers and also enhances energy security, making irrigation more sustainable and environmentally friendly.

The PM KUSUM Scheme comprises three main components, each designed to address specific aspects of promoting solar energy adoption in agriculture. Component A focuses on the installation of grid-connected solar plants, Component B involves the installation of standalone solar pumps, and Component C provides financial support for grid-connected agricultural pumps. These components aim to diversify renewable energy sources in the agricultural sector and maximize the benefits of solar energy for farmers. Overall, the PM KUSUM Scheme represents a significant step towards achieving SDG7 by promoting affordable and clean energy for agricultural irrigation. By leveraging solar energy, the scheme not only contributes to environmental sustainability, but also enhances the livelihoods of farmers and economic development in rural areas.

4.1.3 Impact of Renewable Energy Cooperatives in the Transition from Fossil to Renewable Energy

The third research question examines the potential of energy cooperatives to support the transition from fossil fuel-based to solar irrigation systems.

The Dhundi Solar Pump Irrigators' Cooperative Enterprise (SPICE) is a pioneering initiative that began in Dhundi Village, Gujarat, in early 2016. Initially facing challenges in convincing farmers to adopt solar technology due to skepticism about its reliability, the cooperative eventually succeeded in registering under the Gujarat Cooperative Societies Act with the help of the International Water Management Institute (IWMI) and the Department of Cooperation.

Led by 72-year-old farmer Dhundi Phodabhai Parmar and five others, SPICE employs solar pumps, shifting from diesel to solar energy. By adopting net metering, they sell surplus power to the Madhya Gujarat Vidyut Company (MGVCL) under a 25-year power purchase agreement (PPA). Members also receive bonuses for green energy and groundwater conservation.

By December 2016, the cooperative had earned over INR 1,60,000 from energy sales. With a combined capacity of 56.4 kilowatt-peak (kWp), the cooperative's six solar pumps have the ability to produce around 85,000 units of energy each year. Members use some of this energy for irrigation and inject the surplus into the grid, earning revenue from energy sales. Solar power offers significant advantages over diesel and subsidized grid power, including cost-effectiveness, reliability, and uninterrupted supply during daytime.

Member of Dhundi cooperative: "When I became a member of this cooperative, my expenses got reduced as I did not need to pay the huge amount for diesel."

Member of Dhundi Cooperative: "Solar pumps substantially reduce operational costs compared to diesel pumps. In addition to this I also found an alternative source of income as
well by selling extra electricity to the government. By earning extra income, I was able to buy my kid a bicycle."

The cooperative's model, which involves farmers pooling resources to establish a microgrid, deserves recognition and possibly better feed-in tariffs compared to other solar power initiatives. In Dhundi Village, most households belong to the Darbar Community, with many being marginal farmers. Six members of the community have installed solar plants, with capacities ranging from 8 kW to 10.8 kW. Operational costs for energy generation are minimal, and farmers receive training for basic maintenance of the solar systems. Overall, the Dhundi Solar Pump Irrigators' Cooperative Enterprise represents a sustainable and innovative approach to agriculture and energy production, benefiting both farmers and the environment.

In investigating the potential contribution of energy cooperatives to the shift from fossil fuel-dependent to solar irrigation systems, several significant insights have emerged. This cooperative demonstrates a novel concept called Solar Power as a Remunerative Crop (SPaRC). SPaRC leverages solar energy to address several critical issues in Indian agriculture and energy sectors. The Dhundi cooperative uses solar pumps for irrigation and sells surplus solar energy back to the local power distribution company, MGVCL, under a 25-year power purchase agreement. This arrangement ensures a stable income for farmers from solar power sales, supplementing their agricultural earnings. The cooperative model offers multiple benefits as farmers earn additional income from selling surplus solar power, which is seen as a low-risk and steady source of revenue, unlike traditional crops that are vulnerable to weather and market fluctuations. By adopting solar power, farmers can also reduce their dependence on heavily subsidized grid power. This shift can significantly lower the financial burden on power DSOs and the government, which currently provide extensive electricity subsidies to the agricultural sector. Solar power reduces the carbon footprint of agriculture by replacing diesel pumps, which are both expensive and polluting.

Dhundi cooperative member -" With the money we've made from selling electricity since last year, we've also started saving for my son's college education. Solar power has really made a difference for our family"

Dhundi Cooperative member: "Previously, irrigating one time cost me Rs. 250 per beegha (1.75 beegha is one acre), but now it's free, and I can also sell the excess power. The best part is that I didn't have to spend any money to earn this additional income. We initially thought the solar panels would take up a lot of land, but later we discovered that crops like spinach and eggplants can still be grown underneath them."

Dhundi NGO Executive: "Additionally, it encourages water conservation by making the energy cost of pumping groundwater explicit. Solar pumps provide a reliable and uninterrupted power supply during daylight hours, unlike grid power which is often inconsistent and supplied during inconvenient times. Farmers were motivated to sell surplus electricity to the government, which made farmers more responsible towards the environment and generated other revenue opportunities as well."

Dhundi NGO Executive: "The community is now more open to renewable energy solutions and sees the benefits."

The adoption of solar energy in irrigation aligns with global trends in renewable energy deployment and supports sustainable development goals by significantly reducing greenhouse gas emissions. The Dhundi model is gaining popularity, with more farmers showing interest in forming similar cooperatives. The initial success has led to increasing willingness among farmers to invest in solar pumps, viewing them as valuable assets for both irrigation and income generation. Farmers now look at solar pumps as valuable assets for both irrigation and income generation.

4.1.4 Interpretation of Results

Electric tube wells are widely used in India for groundwater irrigation, particularly in regions where the water table is deep. These tubewells rely on electric pumps, which are heavily subsidized by farm power policies. The subsidies make electricity cheaper for farmers, but they also contribute to significant carbon emissions due to the high energy consumption required to pump water from deep underground. The deeper the water table, the more energy is required, leading to higher emissions. This situation is exacerbated by the fact that the power grid in many rural areas is still largely dependent on coal and other fossil fuels, which further increases the carbon footprint associated with electric tubewells. Diesel tubewells, on the other hand, use diesel engines to pump groundwater. While they generally emit less carbon compared to electric

pumps, their usage is limited by their unsuitability for accessing deep groundwater. Diesel engines are less efficient at pumping water from significant depths, which restricts their application to areas with relatively shallow water tables. Despite their lower emissions, diesel tubewells still contribute to environmental pollution and incur higher operational costs for farmers due to the fluctuating price of diesel. The total carbon emissions from groundwater irrigation in India arise from the combined use of electric and diesel tubewells. The widespread use of electric tubewells, driven by subsidies and the need to access deep groundwater, results in substantial emissions. The overall impact on the environment from both types of tubewells is significant, highlighting the need for a more sustainable solution. Solarizing groundwater pumps presents a promising opportunity to reduce the carbon footprint of India's irrigation sector. By replacing electric and diesel tubewells with solar-powered pumps, the reliance on fossil fuels and the associated carbon emissions can be drastically reduced. Solar pumps operate using energy from the sun, which is a clean and renewable resource. Implementing solar pumps on a large scale could potentially eliminate the carbon emissions from groundwater irrigation, contributing to a 4-5% reduction in India's annual carbon emissions. This shift not only aligns with global efforts to combat climate change but also promotes energy security and reduces the operational costs for farmers. The transition from diesel to solar energy for irrigation brings significant economic benefits for farmers. Solar pumps substantially reduce operational costs compared to diesel pumps, which require constant fuel purchases. The high initial investment in solar pumps is offset by the long-term savings on fuel and maintenance costs. As solar pumps harness renewable energy from the sun, they provide a free and inexhaustible power source once installed. This leads to a reduction in input costs, allowing farmers to allocate their savings

to other areas of farm management and development. Moreover, solar irrigation systems increase crop yield and enhance farmers' income. The consistent and reliable power supply from solar pumps ensures timely and adequate irrigation, leading to improved crop health and higher productivity. This is particularly beneficial in regions with erratic power supply or where electricity is not readily available. Increased crop yields translate to higher marketable produce, boosting farmers' earnings and contributing to rural economic growth. Solar pumps significantly reduce greenhouse gas emissions compared to diesel pumps, contributing to environmental sustainability. Diesel pumps emit carbon dioxide and other pollutants, exacerbating climate change and air quality issues. In contrast, solar pumps operate without emitting greenhouse gasses, thus mitigating the environmental impact of agricultural practices.

The adoption of solar irrigation aligns with global efforts to combat climate change by reducing the carbon footprint of agricultural activities.

This shift also supports the achievement of SDG7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. By promoting renewable energy sources in agriculture, the transition to solar energy helps to build resilient agricultural systems and reduce dependency on fossil fuels, advancing sustainable development. Government initiatives such as PM-KUSUM play a pivotal role in facilitating this transition. It provides financial incentives and subsidies to farmers for installing solar pumps, making the technology more accessible and affordable. This initiative also includes provisions for setting up decentralized solar power plants, which can feed surplus energy back into the grid, creating an additional revenue stream for farmers.

Table 4 is likely to provide specific data or statistics illustrating the economic and environmental benefits of switching to solar pumps compared to diesel-powered systems, further highlighting the advantages of this transition for farmers in rural India.

Category	Diesel Powered irrigation	Solar powered irrigation
Operational cost	High due to fuel cost	Low as sunlight is free
Maintenance cost	High	Low
Environmental impact	High emission	Zero emission
Profitability	Reduced	Increased
Reliability	Variable	Consistent
Adoption support	High initial cost, credit access issues	Technical expertise,energy storage, policy coordination
Economic benefit	Limited	Increased from energy sales, increased sales,reduced cost
Environmental benefit	Negative	Positive, reduced carbon emissions
Community attitudes	Hesitant	Positive shift towards renewable energy

Table 4: Comparison of Diesel-based irrigation and solar-based irrigation

In understanding and analyzing the effectiveness between the PM-KUSUM scheme and Dhundi cooperation initiative, it is visible that the initiative launched by the government involves many layers of bureaucracy, which can make planning and execution slow and complex. In contrast, Renewable Energy Cooperatives (RECs) involve beneficiaries (like farmers) from the very beginning, making them more motivated and dedicated to the project's success.

Aspect	PM KUSUM	Renewable energy cooperatives
Planning and approval	Managed by various government departments, leading to delays	Initiated and planned by the community, ensuring quick decisions
Execution	Involves central and state governments, local authorities, and contractors	Carried out by the beneficiaries, involving local resources and management

Motivation and commitment	Less direct involvement, potentially lower motivation.	High motivation due to direct involvement and personal stake
Communication	Multiple layers, slower communication	Direct communication, faster decision making
Solution tailoring	General solution that may not account for local specifics	Solutions tailored to specific community needs
Sustainability	Dependent on external contractions, possibly less sustainable	High maintenance due to local management and maintenance.

Table 5 : Comparison of PM KUSUM and Renewable Energy Cooperatives

4.2 Conclusion

Renewable energy cooperatives, such as SPICE, further support this transition by fostering community engagement and collective investment in solar energy projects. These cooperatives enable farmers to pool resources, share knowledge, and benefit from economies of scale, enhancing the adoption of solar pumps and other renewable energy technologies in agriculture. The findings are consistent with previous studies that highlight the economic and environmental advantages of renewable energy adoption in agriculture (Reference). Research indicates that renewable energy sources, such as solar power, are not only environmentally sustainable but also economically viable for agricultural applications. The success of PM-KUSUM and SPICE aligns with global trends in renewable energy deployment, underscoring the potential of solar energy to drive sustainable development in the agricultural sector.

Economically, solar pumps reduce operational costs for farmers by eliminating the need for costly diesel fuel and reducing maintenance expenses. This shift not only improves the profitability of farming operations but also increases crop yields due to the reliability and consistency of solar-powered irrigation systems. Consequently, farmers experience enhanced incomes and greater financial stability. Environmentally, the use of solar pumps drastically reduces greenhouse gas emissions compared to diesel pumps. This transition contributes significantly to environmental sustainability by lowering the carbon footprint of agricultural practices. It aligns with global efforts to combat climate change and supports the achievement of SDG7, which aims to ensure access to affordable, reliable, sustainable, and modern energy for all. The successful implementation of solar irrigation systems through government initiatives and cooperatives can serve as a model for other regions. It demonstrates the potential for renewable energy to address the dual challenges of energy access and environmental sustainability in the agricultural sector in India. Initiatives like the PM-KUSUM Scheme have provided a ray of hope. By subsidizing the installation of solar irrigation pumps, the scheme promotes cleaner energy sources, reduces operational costs, and enhances energy security for farmers. Solar pumps offer a sustainable alternative to diesel-powered pumps, contributing to environmental sustainability and economic viability in agriculture.

The success of initiatives like the Dhundi Solar Pump Irrigators' Cooperative Enterprise exemplifies the potential of energy cooperatives in driving the transition to renewable energy. By pooling resources to establish solar microgrids, farmers can generate additional income from surplus solar power sales, supplementing their agricultural earnings and reducing reliance on subsidized grid power. However, challenges remain, including the high upfront costs of solar infrastructure, limited access to affordable credit, and the need for technical expertise in maintenance. Collaborative efforts from government bodies, financial institutions, and stakeholders are crucial to overcome these hurdles and ensure the effective implementation and scalability of such schemes.

The success of PM-KUSUM and SPICE underscores the importance of supportive policies and community-based approaches in promoting renewable energy in agriculture. PM-KUSUM's financial incentives and technical support make solar technology more accessible, while SPICE's cooperative model fosters community engagement and collective investment, enhancing the scalability and impact of solar energy initiatives.

This study highlights the critical role of policy makers, researchers, and practitioners in advancing sustainable development goals. Policy makers must continue to support and expand initiatives like PM-KUSUM, providing necessary financial and technical assistance to farmers. Researchers should conduct further studies on the long-term impacts of solar irrigation systems on agricultural productivity and sustainability. Practitioners, including renewable energy cooperatives, should promote community engagement and collective benefits to ensure widespread adoption and success.

Overall, the transition to solar energy in India's irrigation practices presents a viable pathway to achieving economic prosperity and environmental sustainability in the agricultural sector. The findings are consistent with global trends and previous studies that emphasize the advantages of renewable energy adoption in agriculture. By continuing to support and expand renewable energy initiatives, India can strengthen its agricultural sector, reduce its carbon footprint, and advance towards its sustainable development goals.

Policy makers should continue to support and expand initiatives like PM-KUSUM by providing financial incentives to reduce the upfront costs of solar irrigation systems for farmers. This can be achieved through increased subsidies, offering low-interest loans, and providing grants to make solar technology more accessible. It is essential to enhance technical support by establishing robust systems that assist farmers with the installation, maintenance, and efficient operation of solar pumps. This can be done through training programs and the establishment of local service centers to ensure that farmers can effectively use and maintain the technology.

Policy makers should encourage collaboration between the PM-KUSUM initiative, which follows a top-down approach, and the SPICE initiative, which follows a bottom-up approach. This synergy can ensure comprehensive policy development and implementation, leveraging the structured support of PM-KUSUM with the direct beneficiary involvement characteristic of SPICE. Furthermore, extensive information campaigns should be developed and implemented to educate farmers about the benefits and processes associated with solar irrigation systems. Utilizing multiple platforms such as social media, local radio, community meetings, and agricultural extension services can help reach a broader audience.

Proactively developing policies for the safe disposal and recycling of solar waste is crucial to prevent future environmental challenges. This includes setting up e-waste collection centers and promoting research into sustainable disposal methods. Researchers should perform comprehensive studies on the long-term impacts of solar irrigation systems on crop yields, soil health, and water usage. This will provide a deeper understanding of how solar technology affects farming practices over time. It is important to investigate the sustainability of solar irrigation systems, including their lifecycle, environmental impact, and economic viability. Research should also focus on integrating these systems with other renewable energy sources and smart irrigation practices.

Researchers should explore new technologies and innovations that can enhance the efficiency and effectiveness of solar pumps. This includes advancements in battery storage, smart grid integration, and automated irrigation systems. Practitioners should promote the formation of cooperatives that allow farmers to collectively invest in and benefit from solar irrigation systems. This approach can enhance community involvement, reduce individual costs, and ensure better maintenance and management of the systems. Facilitating the sharing of resources and knowledge among cooperative members can enable better access to financing, technical support, and market opportunities. Practitioners should encourage the exchange of best practices and success stories among farmers. Demonstration projects and field visits can be used to show the practical benefits and operational aspects of solar pumps.

Organizing regular training sessions for farmers and cooperative members on the technical aspects of installing, operating, and maintaining solar irrigation systems is essential for ensuring effective use of the technology. Practitioners should encourage the exchange of best practices and success stories among farmers. Demonstration projects and field visits can be used to show the practical benefits and operational aspects of solar pumps. Organizing regular training sessions for farmers and cooperative members on the technical aspects of installing, operating, and maintaining solar irrigation systems is essential for ensuring effective use of the technology.

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Appendix A

Dimension/Theme	**Code**	**Sample Quote**
Irrigation Practices	Dependence on Monsoon and Diesel Irrigation	"We are dependent on the Monsoon. Since it is highly unpredictable therefore Diesel irrigation is by far the best irrigation solution."
Challenges in Irrigation	Quality and Reliability of Electricity	"Because of poor quality and unreliable electricity, we have to rely only on Diesel irrigation."
Economic impact	Economic Impact of Diesel Prices	"Continuous price increase in fossil fuel like diesel reduced the profit."
Economic Impact on Farmers	Income Reduction	"Continuous price increase of Diesel and high maintenance cost reduced the income of farmers."
Electrification Issues	Current Electrification Scenario	"Electrification has been done in our area but the major issue is reliability, quality and affordability of electricity. Power for irrigation is supplied late at night and we

		have to do irrigation late at night which is risky because of the risk of snake and scorpion bites etc."
Electricity Issues	Unreliable and Poor Quality of Electricity	"Since the electricity we are getting is unreliable (only for 7-8 hours), poor quality (as the voltage is extremely low and not sufficient to run the irrigation pump) and expensive so why should we pay the electricity bill if it doesn't serve our purpose of irrigation."
Health and Environmental Impact	Emissions and Pollution	"While running the diesel engine, it emits lots of emissions and gasses which are not good for our health and pollute the environment, but we don't have any option except using diesel for irrigation."
Health and environment Impact	Awareness of Negative Health Effects	"Yes, we are aware of the negative effects but currently we don't have an alternative."
Interest and awareness	Interest in Government Initiatives	"Yes, absolutely."
Government Policies (PM KUSUM Yojana)	Awareness and Application	"Yes, it is a good initiative started by the government of India in which solar pumps

		are being installed in farmer’s place and subsidy is also given."
Challenges in the application process	Benefits and Difficulties	"First of all, awareness. I was not aware of such government policy before. There are some middlemen also who were charging fee for your application. But I later realised that I could apply through the Internet."
Energy Cooperatives	Introduction and Membership	"I was approached by the team members of one of the NGOs who took the initial workshop and guided me about the process of becoming the member of cooperative."
Energy Cooperatives	Benefits of Membership	"When I became a member of this cooperative, my expenses got reduced as I did not need to pay the huge amount for diesel." Synergy between PM-KUSUM and RECs
Synergy between PM-KUSUM and RECs	Comparative Analysis	"PM-KUSUM is a policy implemented by the government therefore lot of bureaucratic layers were involved in planning and execution. However, in RECs beneficiaries are involved from the beginning of the process and motivated and inspired and showed more sincerity than the people involved in PM-KUSUM."
Transition from Fossil Fuels to Solar	Farmers' views on how solar pumps contribute to achieving affordable and clean energy.	"Solar energy has made irrigation affordable and sustainable for us."

Role of Government Initiatives How farmers learned about the PM-KUSUM scheme and their motivations to participate.	How farmers learned about the PM-KUSUM scheme and their motivations to participate.	"We heard about the PM-KUSUM scheme through village meetings and local officials." Process of Receiving Support
Role of Government Initiatives	Types of support received from the government (financial, technical, training).	"We received a subsidy which covered a large part of the installation costs."
Role of Government Initiatives	How government support helped in the transition to solar energy.	"Government support was crucial in making the switch to solar energy feasible."
Role of Energy Cooperatives	Challenges faced by farmers in participating in an energy cooperative.	"Sometimes there are coordination issues within the cooperative."
Role of Energy Cooperatives	Suggestions for additional support that cooperatives	"More training sessions and financial support would be beneficial."

	can provide to aid transition to solar energy.	
Objective-Oriented Questions	Comparison of reliability and availability of solar energy versus fossil fuel-based systems.	"Solar energy is more reliable than diesel pumps, especially during peak irrigation seasons." Environmental Benefits of Solar Irrigation
Economic Impact of Solar Energy	Positive economic outcomes from selling electricity and easier irrigation with solar energy.	"As I started selling electricity, I was able to buy a cow within a year. I have sold electricity worth 90,000 rupees since May 2016 and am selling milk as well. We hope to carry it on which can enable us to send our two kids to private schools in the years to come. Solar energy has given us hope.", "Irrigating our farms has now become far easier and we now, grow vegetables such as tomato which need many irrigations.
Objective-Oriented Questions	Observed environmental benefits since transitioning to solar-powered irrigation.	"We have noticed a significant reduction in pollution and fuel consumption."
Benefits of Membership	Advantages of being a member of energy cooperatives, such as cost reduction and technical support.	"When I became a member of this cooperative, my expenses got reduced as I did not need to pay the huge amount for diesel."
Comparative Analysis	Comparison between government policies like	"PM-KUSUM is a policy implemented by the government therefore lot of

	PM-KUSUM and initiatives like Renewable Energy Cooperatives (RECs).	bureaucratic layers were involved in planning and execution. However, in RECs beneficiaries are involved from the beginning of the process and motivated and inspired and showed more sincerity than the people involved in PM-KUSUM."
Impact of Diesel Pumps	Environmental and noise pollution reduction due to the absence of diesel generators in the village.	"Today, our village is free of noise because there are no diesel generators. It is a big relief."
Economic Impact of Solar Energy	Positive economic outcomes from selling electricity and easier irrigation with solar energy.	"As I started selling electricity, I was able to buy a cow within a year. I have sold electricity worth 90,000 rupees since May 2016 and am selling milk as well. We hope to carry it on which can enable us to send our two kids to private schools in the years to come. Solar [energy] has given us hope.", "Irrigating our farms has now become far easier and we, now, grow vegetables such as tomato which need many irrigations."
Economic Impact of Solar Energy	Financial benefits and increased agricultural productivity through solar-powered irrigation.	Previously, irrigating one time cost me Rs. 250 per beegha (1.75 beegha is one acre), but now it’s free, and I can also sell the excess power. The best part is that I didn’t have to spend any money to earn this additional income. We initially thought the solar panels would take up a lot of land, but later we discovered that crops like

		spinach and eggplants can still be grown underneath them

Table 6: Thematic Coding of the interviews with the farmers, NGO executives and the beneficiaries of PM-KUSUM and Dhundi Energy Cooperative

Appendix B

Interviewee Category	Who were interviewed	How many Contacts were obtained
Farmers individual from various communities	Individual farmers from various communities	10
Energy cooperatives members	Members of energy cooperatives i.e. Dhundi cooperatives	5
NGOs executives	Local and regional NGOS officials involved in PM KUSUM and other initiatives	5

Table 7: No of interviewees and category of interviewees

Appendix C

Interview questions

1. What type of irrigation system were you using before switching to solar pumps?

2. What were the major challenges you faced with your previous fossil fuel-based irrigation system in terms of cost, reliability, and environmental impact?

3. How has the switch to solar energy impacted your irrigation costs and overall farming expenses?

4. In your opinion, how has the adoption of solar pumps contributed to achieving affordable and clean energy (SDG7) in your farming practices?

5. How did you learn about the PM-KUSUM scheme, and what motivated you to participate?

6. Can you describe the process you went through to receive support from the PM-KUSUM scheme?

7. What kind of support (financial, technical, training) did you receive from the government under the PM-KUSUM scheme?

8. How has government support facilitated your transition to solar energy for irrigation?

9. What improvements or additional support would you suggest for government schemes to better assist farmers in adopting solar energy?

10. Are you a member of any energy cooperative like the Dhundi Solar Pump Irrigators' Cooperative? If yes, can you describe your experience?

11. How has being part of a cooperative impacted your use of solar energy for irrigation?

12. What are the benefits and challenges you have experienced by participating in an energy cooperative?

13. Do you believe that cooperatives play a significant role in promoting solar energy among farmers? If so, how?

14. What additional support do you think cooperatives can provide to help farmers transition from fossil fuels to solar energy?

15. How has the reliability and availability of solar energy compared to your previous fossil fuel-based systems?

16. What environmental benefits have you observed since transitioning to solar-powered irrigation?

17. Have you noticed any changes in community attitudes towards renewable energy since you adopted solar irrigation?

18. What future improvements or innovations in solar irrigation technology would benefit your farming practices the most?