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Solar for Irrigation

A Comparative Assessment of Deployment Strategies

ANNE RAYMOND AND ABHISHEK JAIN

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CEEW Report

January 2018

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A report on 'Solar for Irrigation: A Comparative Assessment of Deployment Strategies'

Cover image: Pixabay

This report has been peer-reviewed by Ms Sudatta Ray (Standford University), Mr Nilanjan Ghosh (GIZ), and Mr Vaibhav Chaturvedi (CEEW).

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The Council on Energy, Environment and Water (http://ceew.in/) is one of South Asia's leading not-for-profit policy research institutions. CEEW uses data, integrated analysis, and strategic outreach to explain–and change–the use, reuse, and misuse of resources. CEEW addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public.

In 2017, CEEW was once again featured extensively across nine categories in the '2016 Global Go To Think Tank Index Report', including being ranked as South Asia's top think tank (14th globally) with an annual operating budget of less than US$5 million for the fourth year running. In 2016, CEEW was also ranked second in India, fourth outside Europe and North America, and 20th globally out of 240 think tanks as per the ICCG Climate Think Tank's standardised rankings. In 2013 and 2014, CEEW was rated as India's top climate change think tank as per the ICCG standardised rankings.

In over seven years of operations, CEEW has engaged in more than 180 research projects, published well over 110 peer-reviewed books, policy reports and papers, advised governments around the world over 400 times, engaged with industry to encourage investments in clean technologies and improve efficiency in resource use, promoted bilateral and multilateral initiatives between governments on more than 50 occasions, helped state governments with water and irrigation reforms, and organised more than 210 seminars and conferences.

CEEW's major projects on energy policy include India's largest energy-access survey (ACCESS); the first independent assessment of India's solar mission; the Clean Energy Access Network (CLEAN) of hundreds of decentralised clean energy firms; India's green industrial policy; the $125 million India–U.S. Joint Clean Energy R&D Centers; developing the strategy for and supporting activities related to the International Solar Alliance; modelling long-term energy scenarios; energy subsidies reform; decentralised energy in India; energy storage technologies; India's 2030 renewable energy roadmap; solar roadmap for Indian Railways; clean energy subsidies (for the Rio+20 Summit); clean energy innovations for the rural economy; solar for health care; and renewable energy jobs, finance, and skills.

CEEW's major projects on climate, environment, and resource security include advising and contributing to climate negotiations (COP-23) in Bonn, especially on formulating the guidelines of the Paris Agreement rule book; pathways for achieving NDCs and mid-century strategies for decarbonisation; assessing global climate risks; heat-health action plans for Indian cities; assessing India's adaptation gap; low-carbon rural development; environmental clearances; modelling HFC emissions; business case for phasing down HFCs; assessing India's critical mineral resources; geoengineering governance; climate finance; nuclear power and low-carbon pathways; electric rail transport; monitoring air quality; business case for energy efficiency and emissions reductions; India's first report on global governance, submitted to the National Security Adviser; foreign policy implications for resource security; India's power sector reforms; resource nexus, and strategic industries and technologies for India's National Security Advisory Board; the Maharashtra–Guangdong partnership on sustainability; and building Sustainable Cities.

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Anne Raymond received M.S. degrees in Mechanical Engineering and Technology and Policy from the Massachusetts Institute of Technology in June 2017. She spent the following summer and fall as an intern at Council on Energy, Environment and Water in New Delhi, where her stay was supported by the MIT International Science and Technology Initiatives (MISTI). Anne's academic work at MIT focused on energy, materials, and manufacturing processes, as well as the environmental impact of recycling. Anne is more broadly interested in how advances in technology, particularly those that could enable a more sustainable future, are incorporated into policy and business decisions. Before starting graduate school, Anne worked as a science teacher, an analytical chemist, and on the management team of a start-up providing off-grid electricity access. She is fortunate to have lived and worked in several US states, Africa, and now India. Anne holds a B.A. in Chemistry from Dartmouth College and currently lives in Boston, Massachusetts.

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Abhishek Jain is a Senior Programme Lead at the Council on Energy, Environment and Water. He leads the Council's research and outreach in the area of 'energy access'. His research focuses on energy access for household consumption, community-based, and productive applications, fossil fuel subsidies' reform, and circular economy. He is keenly exploring avenues for the use of information and communications technology (ICT) and big data to inform public policy.

Over the past six years, Abhishek has worked on multiple issues at the confluence of energy, economics, environment and sustainable development. Most recently, he has co-led the largest energy access survey in India. He also conducted the first independent evaluation of the world's largest direct benefit transfer scheme. He has researched and published in the areas of energy access, clean cooking energy, rationalisation of LPG and kerosene subsidies, deployment strategies for solar pumps, and electricity sector reforms for India, to name a few. He regularly presents at various national and international forums, and writes in leading national dailies.

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Executive Summary

Solar pumps could improve access to sustainable irrigation for farmers in India. The central government is committed to supporting solar pumps through capital subsidy schemes. However, the adoption rate of solar pumps under the current policy has been slow, raising the need to research into alternative strategies to promote the adoption of solar-powered irrigation systems (SPIS). An effective approach will involve multiple perspectives, including the economic and other preferences of farmers, financiers and policymakers. In this report, we focus on the economics of solar pump adoption for farmers and the government under different deployment approaches. We develop a financial model, and apply it to four key questions of interest to policymakers as they consider the costs and benefits of different irrigation pump deployment approaches.

Key findings

Connecting solar pumps to the electric grid is expensive for the government and benefits farmers lesser than subsidies for the purchase of solar pumps. The cost to the government to subsidise a 3HP stand-alone solar pump at 60 per cent, or to provide a grid connection to an existing solar pump and pay the farmer a feed-in tariff for surplus energy over 15 years is approximately equal. However, the farmer's cost under the capital subsidy scenario is 53 per cent lesser than that in the grid-connected case, despite revenues from the feed-in tariff.

Connecting solar pumps to the grid may provide some additional revenue to solar pump owners. However, they would prefer selling water using surplus energy, should there be a local demand. Equivalent revenue that a farmer can gain for such pumping service is INR 20 per kWh, which is much higher than the feasible feed-in-tariff. However, not all the surplus energy can be utilised for selling water locally, as the demand is also seasonal and intermittent.

Water-as-a-service using solar pumps by village level entrepreneurs is a promising model to improve both the utilisation of solar pumps, and provide irrigation access to marginal farmers. The viability of solar pump sharing and the significance of the revenue from it remain sensitive to the timing of local irrigation needs. **In areas with a dominance of diesel pumps for renting or selling water, solar-based water-as-a-service model could have a payback of two to four years.**

Encouraging pump sharing could be an opportunity for the government to increase the utilisation of solar pumps. It would increase the impact of government support while creating a market-based solution for efficient and judicious use of the ground water.

Individually owned solar pump deployment should focus on farmers currently deprived of grid connections. Farmers receiving reliable subsidised electricity from the grid would not find a stand-alone solar pump attractive even at 60 per cent capital subsidy. The government should **target marginal farmers with smaller pumps, particularly farmers planning greater numbers of cropping cycles, or having more irrigation days each year.**

Promoting solar pumps through interest rate subvention, rather than capital subsidy, improves the viability of rapid pump deployment from the government's perspective, and can benefit farmers by supporting greater access to solar pumps to more people at a faster pace. Implementation of this approach is particularly dependent on long-term commitment from the government and financiers who should be willing to provide loans.

Finally, the government should continue to support solar pumps in the country, but should do so in a manner that seeks not just to attain a set number of deployed irrigation pumps each year, but rather to promote deployment scenarios that are suitable to the given context. Only then, we would be able to effectively harness the potential of a decentralised technology, to maximise the socio-economic impact, and minimise potentially harmful environmental impacts.

1. Introduction

Irrigation in India today is almost entirely reliant on electric and diesel pumps. Of the nearly 30 million irrigation pumps in use throughout the country, about 70 per cent run on grid electricity, 30 per cent are powered by diesel, and only 0.4 per cent are solar (Agrawal and Jain, 2015; MNRE, 2017a). The annual fossil fuel use associated with diesel and electric pumps amounts to more than four billion litres of diesel, and 85 million tonnes of coal for electricity generation (KPMG, 2014). The demand for irrigation far exceeds the available pumping capacity. In 2016, only 48 per cent of the net sown area in the country was irrigated, leaving more than half of all the farmland to rely on rainfall (Department of Agriculture, Cooperation and Farmers' Welfare, 2016). Rapidly growing population, coupled with unreliable precipitation patterns and extreme temperatures wrought by climate change impose additional pressure on agricultural productivity in the country. Therefore, improving access to irrigation, while reducing greenhouse gas emissions, has become our national priority.

To meet the dual objective, solar powered pumps are emerging as an alternative solution to those powered by grid electricity and diesel. Diesel and electric pumps have low capital costs, but their operation depends on the availability of diesel fuel or a reliable supply of electricity. Although the government heavily subsidises agricultural grid connections, grid electricity in rural India is usually intermittent, fraught with voltage fluctuations, and the waiting time for an initial connection can be quite long (Banerjee, Barnes, Singh, Mayer and Samad, 2015). Solar pumps provide freedom to farmers from these constraints, by giving a reliable access to irrigation on most occasions. However, some of the recent field studies have indicated that solar pumps have not been able to replace the electric or diesel pumps entirely (Shakti Sustainable Energy Foundation, 2018). For a few days in a year, farmers complement other pumps with solar pumps. Looking at the economics, the capital cost of solar pumps is high, but on a life-time cost basis, solar pumps may offer savings for farmers due to their low operating expenses.

The Government of India has set ambitious targets for expanding the country's renewable energy generating capacity, and in 2010 launched the Jawaharlal Nehru National (JNN) Solar Mission. In 2014, as part of this mission, the Ministry of New and Renewable Energy (MNRE) outlined the Solar Pumping Programme for Irrigation and Drinking Water, which sought to promote the adoption of solar pumps over five years (MNRE, 2014b). Implementation of the programme involved two financing schemes. First, farmers received a central financial assistance (CFA) of 30 per cent of the benchmark cost of the pump, and possible additional subsidies at the state level. The second, credit-linked scheme, involved 40 per cent capital subsidy from MNRE, 20 per cent beneficiary contribution, and the remaining amount extended as a loan implemented through the National Bank for Agriculture and Rural Development (NABARD)(MNRE, 2014a).The initial capital subsidy scheme aimed at supporting 100,000 pumps in 2014, and one million by 2020, and the credit-linked scheme through NABARD targeted an additional 10,000 irrigation pumps by 2016.

The number of solar pumps in India is increasing, with about 130,000 pumps installed since 2014 when the scheme started, though progress is well below the goals of the subsidy programme (MNRE, 2017a, 84). In March 2017, MNRE closed the NABARD credit-linked subsidy scheme and set modified capital subsidy rates[1] (MNRE, 2017c). It remains to be seen whether the capital subsidy programme will prove effective in encouraging farmers to buy and use solar pumps in the long run. **The slow adoption of solar pumps over the past three years, however, demonstrates the need for a better understanding of factors that impact how farmers choose among irrigation options available to them, and research into possible alternative strategies**

1 The capital subsidy rates for 2017-2018 are 30 per cent for pumps under 1HP, 25 per cent for 1-3HP, and 20 per cent for pumps 3-5HP.

to promote solar pumps. Jain and Shahidi (2018) write about the farmers' perspectives of choosing irrigation technologies and their views on adopting solar pumps, using a primary survey and set of focused group discussions (FGDs).

A recent article has also drawn a brief comparison of different solar deployment approaches for irrigation, namely grid-connected individual solar pumps, grid-connected solar pumps under a cooperative model, capital-subsidy supported individual solar pumps and solarisation of segregated agricultural feeders (Shah, Durga, Rai, Verma, and Rathod, 2017). However, other researchers have expressed alternative opinions, criticising the bias in the comparative analysis (Sahasranaman, M, Bassi Varma and Ganguly, 2017). As different deployment approaches of solar for irrigation emerge, there is a need to critically analyse them to help policymakers arrive at informed choices for deployment in any given context.

One reason for the emergence of these deployment approaches is the high capital cost of technology, which is a barrier to its adoption. Individual solar pump prices range from INR 85,000 to INR 100,000 per horsepower (HP), whereas a conventional pump of a similar size can be purchased for ten times less (MNRE, 2017b). However, the operating cost of solar pumps is low, and several studies conclude that from a life-cycle cost perspective, solar pumps are better for farmers than diesel pumps (Agrawal and Jain, 2015; GIZ Indo-German Energy Programme, 2013; KPMG, 2014). Though these results are encouraging, the benefit of choosing solar over diesel for a particular farmer depends on factors such as the estimated lifetime of the system, utilisation of the pump, the price of the diesel fuel, and the availability of finance.

Another factor to consider is the economic outcome for the government. Isolated pilot studies can rely on external support for proof-of-concept, but the sustainability of a countrywide programme requires a balance between farmers' incentives to adopt and the government's ability to support solar-powered irrigation in a budget-conscious manner. An example of such an approach is the budget-neutral opportunity proposed by Agrawal and Jain (2015). The authors propose that the government could avoid subsidy for new subsidised irrigation connections and instead, support solar pumps.

The objective of this work is to explore economically attractive approaches –from both the farmers' as well as the government's perspectives – to promote the adoption of solar pumps, and to assess the sensitivity of economic outcomes to variations in conditions across the country. We first develop an economic model of the variables impacting the costs and revenues associated with different types of pumps, and then apply it to a series of deployment scenarios. We conduct economic assessment across the following scenarios:

i. Government-run community pump providing water at a flat monthly tariff;

ii. Farmer renting a pump or purchasing water from neighbour;

iii. Farmer owning an electric pump having electricity at subsidised tariff;

iv. Farmer owning a diesel pump;

v. Farmer owning a stand-alone solar pump;

vi. Grid-connected solar pump with surplus energy fed back to the distributor at a feed-in tariff;

vii. Stand-alone solar pump with surplus water or electricity sold to neighbours.

Our results, and the continued use of this type of scenario modelling can guide decision-making on meeting the nation's ambitious goals for renewable energy use in agriculture. and improve farmers' access to irrigation. Our analysis addresses the following four key policy-relevant questions:

1. What are the economic outcomes for farmers and the government under different solar pump deployment scenarios? How do they compare with conventional pumping methods?
2. Is water-as-a-service using solar pumps a viable business model?

3. Could the government support through interest subvention, rather than capital subsidies, enhance a rapid scale-up of solar pump adoption in India?
4. To what extent does a decrease in the cost of pumps and solar panels improve the competitiveness of solar pumps compared to diesel or electric pumps?

While this report focuses on the economic outcomes for the government and farmers for different irrigation approaches, it is important to note that a farmer's preference may not always align with long-term economic outcomes. Beyond economics, factors such as perceptions of solar pump performance and reliability, familiarity with conventional pumps, availability of capital, and the expected future grid connectivity may impact a farmer's choice of irrigation method (Jain and Shahidi, 2018). Though this work approaches solar pumps from an economic perspective, the policy geared towards promoting solar pumps must also account for non-monetary preferences.

The rest of the report is organised across several sections. In Section 2, we elaborate on the methodology followed for the research and analysis, describe the underlying economic model, and discuss limitations of the research methodology. In Section 3, we present the key findings emerging from the analysis, which is followed by a set of policy recommendations in Section 4. We conclude in Section 5, discussing the way forward for research and solar pumps in India. Finally, the report is complemented with a set of Appendices detailing supportive information useful for interested readers.

2. Methodology

We developed an economic model to calculate the annual cash flow for farmers and the government under different pump deployment scenarios. We discount future cash flows and use the net present value (NPV) of cumulative cash flows to compare the relative viability of options. The model is an MS Excel-based spreadsheet tool designed to provide the user with a flexible means of analysing scenarios and sensitivities. Our assumptions for the model are based on literature review and interviews with farmers. Given any such economic modelling exercise needs a contextualisation for assuming values of various background parameters, we used the background data from the state of Uttar Pradesh. However, the model is designed in a manner that a user can easily update the contextualising variables to set the model for any other region/area. This mainly affects the assumptions around crops sown, ground water level, seasonality, etc. However, **since all the findings from our analysis are used for relative comparison, the findings of this study are applicable pan-India and possibly to other developing countries as well.** We discuss some of the key assumptions in the results and provide more details in the appendices.

We assume that the water that a farmer requires to irrigate his crops is determined by his farm size, rainfall, irrigation efficiency and the type of crops. Holding these factors and, therefore, the annual water requirement constant, we calculate the cost of irrigation under different scenarios. From the farmer's perspective, the model assumes a fresh investment into pumping technology to compare different options, which means the sunk cost of investment already made by a farmer in a pump is not considered. Since the capital cost of existing pumps (diesel and electric) adjusted with depreciation remain a very small component of the overall lifecycle cost, we neglect the existing investment in pumping systems. We assume that a farmer's revenues from crops are the same across pumping options. In practice, crop choices, yields and revenues are influenced by numerous factors in addition to irrigation, and farmers may change their behaviour under different irrigation scenarios. For example, we assume that a farmer will plant the same crops regardless of the irrigation source. However, as the marginal cost of pumping with solar energy is zero, farmers may grow different, more water-intensive crops, or expand their irrigated farm area once they have access to a solar pump (Fishman, Devineni and Raman, 2015). Conversely, under a diesel pump scenario, a farmer may reduce his water use to save money on diesel fuel, thereby reducing the yield of his harvest. This analysis views pump selection through the lens of a farmer, weighing pumping options, with an expectation of the same revenues from crops with each of them. Financiers would be interested in this view, as it provides a conservative assessment of the investment viability.

An economic model provides an insight into the financial costs and benefits of an investment; however, it has limitations that must be considered when interpreting results. First, any model relies on assumptions and simplifications, so it is better used to compare across scenarios rather than calculate absolute numbers. Secondly, the model inputs and assumptions presented in this report have been carefully researched, though they may not hold under all conditions. Finally, model results are not predictors of individual behaviour, as human preferences may not be aligned with economic outcomes. Our model and the following results will be useful for policymakers considering strategies to enhance the adoption of solar for irrigation, but should be used in conjunction with inputs from farmers, financiers and other relevant stakeholders. Two concurrent Council on Energy, Environment and Water (CEEW) reports, for example, present results from interviews with farmers and financiers (Agrawal and Jain, 2018; Jain and Shahidi, 2018).

3. Key Findings

We use an economic model to assess the economic outcomes of entrepreneurs, farmers and the government under different irrigation pump deployment scenarios. These results are structured around the four policy-relevant questions presented in the introduction section. We compare outcomes using the net present value (NPV) of cash flows over 15 years of pump use. Expenditures include capital and operating costs and interest, while revenues are from the sale of water or electricity, and prices increase 4 per cent annually due to inflation. We assume that revenues from agricultural production are constant across each irrigation option, so they are not included in the cash flow. This assessment, therefore, does not measure the overall financial viability of an irrigation option, but can be used to determine its feasibility, compared with alternatives.

Different irrigation options considered for this analysis and their relative advantages and disadvantages (from a farmer's perspective) are summarised in Table 1.

Table 1: Modelled irrigation scenarios from a farmer's perspective

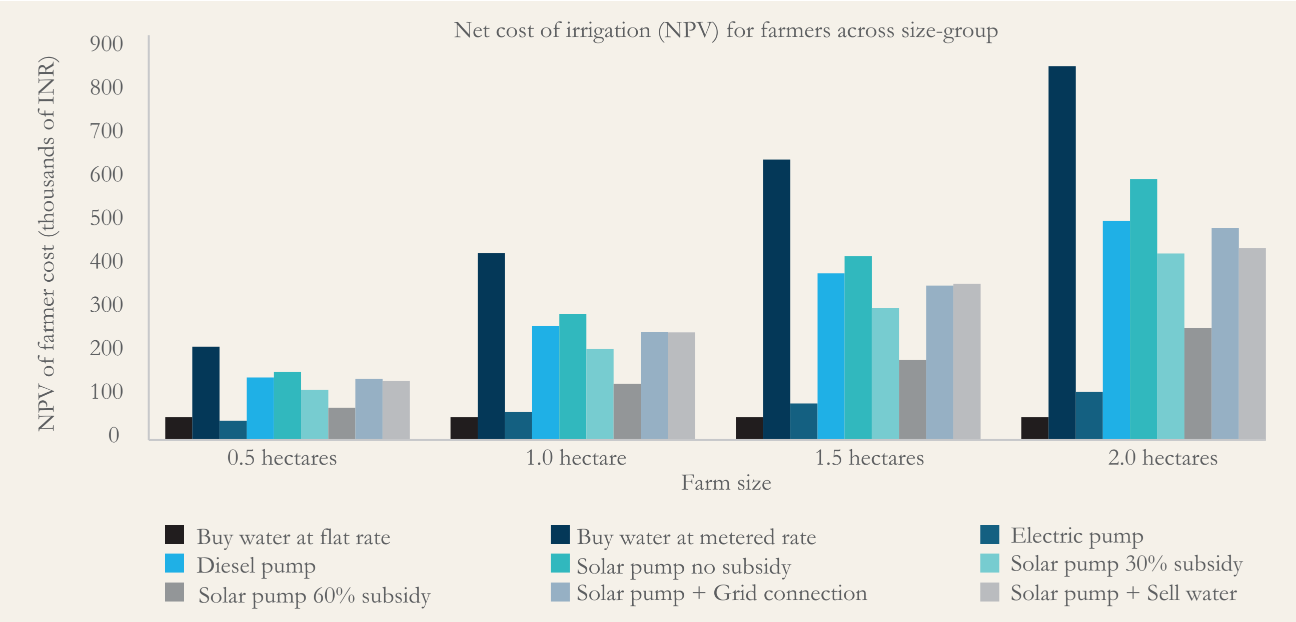
Irrigation scenario	Advantages	Disadvantages
Purchase water from a government pumping station at a flat monthly tariff	Zero capital cost; low operating cost.	Possible only in areas with government pumping stations; limited to no farmer control of water delivery timing and reliability.
Purchase water or rent a pump from a neighbour	Zero capital cost.	High cost of irrigation; tariff subject to local market fluctuations; often causing delays in accessing irrigation (due to queuing).
Own an electric pump	Lowest-cost option if government continues to subsidise the grid connection and electricity.	Waiting time to obtain a connection; intermittency and quality of electricity supply.
Own a diesel pump	Independent from grid; low capital cost; portability of pumps makes it easier to use on fragmented land-holding and to share.	High operating cost; subject to local availability of diesel; creates noise and air pollution.
Own a stand-alone solar pump	Almost no operating cost; clean and efficient pump; government subsidies available.	High capital cost; new technology with limited after-sales support; operating hours limited to daylight.
Own a grid-connected solar pump and sell surplus energy back to the distributor at a feed-in tariff	Almost no operating cost; clean and efficient pump; revenue for the farmer at no additional operating cost.	High capital cost; new technology with limited after-sales support; operating hours limited to daylight; restricted to farmers in areas with grid access.
Own a solar pump and sell water or electricity to neighbours	Almost no operating cost; clean and efficient pump; revenue for the farmer at no additional operating cost.	High capital cost; operating hours limited to daylight; time component of crop irrigation requirements limit sharing; supply of surplus energy varies seasonally.

Source: Authors' Analysis

3.1 How different irrigation options stack for farmers

A farmer's choice of irrigation pump type and size will depend on the upfront and operating cost, pump reliability and myriad local factors including the water table depth, solar radiation, rainfall, crop types, irrigation efficiency, and availability of diesel fuel and grid electricity. The modelled cost to the farmer to irrigate different-sized farms for 15 years using each option is shown in Figure 1. For the cases of solar with a grid connection, or solar with water sales, the NPV is the cost of irrigation minus revenue from selling surplus energy or water. In all the cases of farmer-owned solar pumps, the farmer is assumed to pay 20 per cent of the total capital cost as a down payment and obtain the balance after subsidy as a seven-year loan at 10 per cent interest. For diesel and electric pumps, we assume that the farmer pays the full pump cost in year zero, so does not require financing.

Figure 1: Sale of surplus electricity or water improves the attractiveness of solar compared with diesel, even without capital subsidies.



Source: Authors' Analysis

3.1.1 Subsidy-heavy options are the cheapest for farmers

For a farmer, buying water from the government at a flat monthly rate, or irrigating with an electric pump, are the lowest-cost options. However, these two scenarios are feasible only if the government infrastructure is available, and both rely heavily on government subsidies. The flat rate of water for purchase from government pumping stations is considered as INR 500 per month, based on the information shared by farmers in Uttar Pradesh during Focused Group Discussions conducted by Jain and Shahidi (2018).

3.1.2 Buying water or renting a pump are the costliest options

We also model a scenario in which farmers purchase water from neighbouring pump-owners on a volumetric-price basis. In the field, water is generally priced by volume or by the hour for a particular pump size and water table. However, we have derived a INR/kWh tariff (from per hour rates, prevalent on the ground) to simplify the cost comparisons across different technologies. We considered a metered rate of INR 20 per kWh of pumping energy, which is equivalent to INR 120 per hour for a 3HP pump in a water table of about six to eight meters. This is the highest-cost option for a farmer. At a metered rate, the farmer's irrigation cost is highly sensitive to the water tariff. For example, a 30 per cent change in the pumping tariff results in a 30 per cent change in the farmer's NPV.

Despite the high life cycle cost of purchasing water at a metered rate, it remains a prevalent option for small and marginal farmers[2]. Two surveys of farmers in Uttar Pradesh show that a significant proportion of small and marginal farmers rely on buying water or renting pumps to meet their irrigation needs. Srivastava *et al.* (2009) report that of the 57 marginal farmers surveyed, 68 per cent rely on buying water for all their irrigation needs. This figure drops to 38 per cent for small farmers and 16 per cent for medium or large

2 Small farms are defined as those between one and two hectares of land, and marginal farms have less than one hectare (Srivastava et al. 2009).

farmers. A recent study by CEEW based on survey of 1600 farmers also shows that in Uttar Pradesh about half of small farmers and 60 per cent of marginal farmers buy water or rent a pump (Jain and Shahidi, 2018).

3.1.3 Comparing off-grid options: Solar and diesel pumps

An off-grid farmer can choose to own a diesel or solar pump. Under the modelled assumptions, without government subsidy, a stand-alone solar is less attractive to a farmer than diesel. Whereas **a 30 per cent government subsidy makes ownership of solar pump more attractive for a farmer as compared to owning a diesel pump from a lifetime cost perspective**, under the modelled scenario. This comparison, however, is strongly dependent on the farmer's annual irrigation requirement and on the price of diesel. An increase in the annual pumping hours, which is a function of irrigation requirement and irrigation efficiency, makes solar more attractive than diesel. Similarly, 10 per cent increase in the prevailing price of diesel, for example, yields an 8.6 per cent increase in the NPV of irrigation cost with diesel over 15 years, assuming a 4 per cent annual increase in the fuel price.

Particularly for small and marginal farmers, who mostly rent pumps or buy water at metered rate, while shifting to solar pumps is economically attractive on a lifecycle-cost basis, upfront cost may remain a barrier to solar pump ownership. A 3HP solar pump, for example, costs about INR 260,000, so even with a 60 per cent capital subsidy, the farmer will owe INR 104,000. Farmers in Uttar Pradesh reported spending about INR 25,000 per year on operating expenses, so the capital cost of a solar pump is well beyond the normal working capital of a small farmer. **Thus, government should particularly focus on marginal farmers, through smaller pumps, enhancing their affordability via subsidy and preferential financing support.** Further, innovations in highly efficient, low-cost solar pumps and financing may improve the affordability of pump ownership for marginal farmers.

3.1.4 Strategies to increase solar pump utilisation

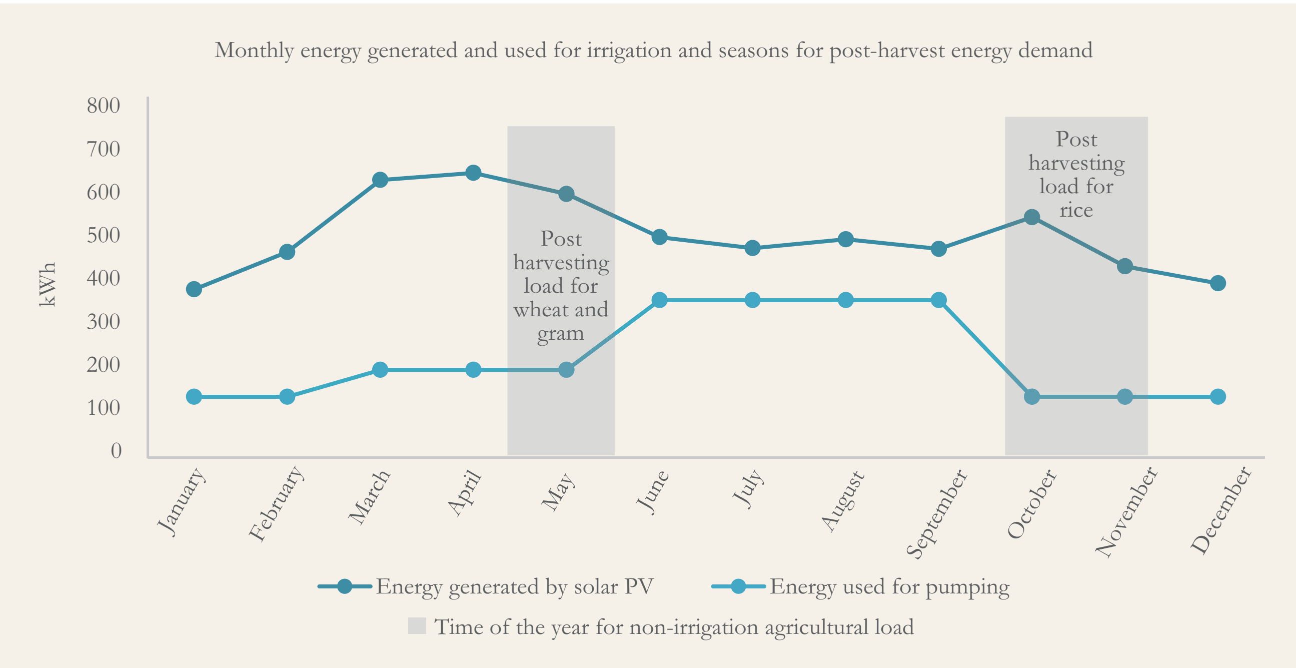
While diesel pumps become more expensive the more they are used, the relative viability of solar pumps improves with higher utilisation. The panels for a solar pump must be sized to meet the power demand of the pump, but on the days when the farmer does not irrigate, the unused energy generated by the panels of a stand-alone solar pump represents unrealised gains from the investment. For example, a farmer with one hectare of land and a 3HP pump will install a 3 kilowatt-peak (kWp) solar array. Depending on rainfall and crops, the farmer will need to run the pump for about 140 days each year to meet his irrigation needs. On the remaining 225 days, both pump and panel are idle, so the utilisation factor of the system is only about 40 per cent low for such a large capital investment. The surplus energy generated under these assumptions is almost 2,000 kWh.

There are three ways to increase a farmer's revenue from a solar pump, assuming that his irrigation needs and agricultural productivity are held constant. One is to connect the pump to the grid so that the farmer can sell surplus energy back to the distribution company for a feed-in tariff, modelled as INR 3.5 per kWh (Uttar Pradesh Electricity Regulatory Commission, 2016). As shown in Figure 1, even without the capital subsidy for solar, the additional income from electricity sales makes grid-connected solar more attractive than diesel for a farmer. A pilot study in Dhundi, Gujarat, has demonstrated that grid-connected solar generates additional revenue for farmers, though the implementation of the pilot is heavily subsidised, so may be hard to scale up (Tripathi, 2016). Given the low cost of grid electricity, a scheme to connect solar pumps to the grid needs to prevent farmers from abandoning or selling their solar panels and simply operating electric pumps. A proposed mechanism to discourage this practice is to provide farmers with a feed-in tariff agreement on the condition that they forego subsidised grid electricity. A downside to this approach, discussed in the next section, is the high cost to the government.

A second strategy for farmers to improve the economics of solar pump ownership is to sell water to neighbours, or rent out the pump. The feasibility of water sales depends on the proximity of other farms, the timing of local irrigation needs, the portability of the pump and the availability of other irrigation options such as government tube wells. Farmers in Uttar Pradesh are already using pumps for both their own irrigation needs and to sell water (Srivastava, Kumar and Singh, 2009). This deployment model is promising, as it maximises pump use, and therefore, the impact of government subsidy, but the extent of pump sharing is constrained by pump portability and the timing of irrigation requirements. Under our conservative set of assumptions, if the pump and panel are sized to meet the farmer's irrigation needs, a farmer can share the equivalent of 10-20 per cent of his or her own pumping demand. Such conservative estimate is based on the assumption that the farmer(s) with whom the pump is being shared grow the same crops with a one-week staggered time period of sowing. In practice, a farmer wishing to make money by selling water could adjust his planting schedule, or find customers growing different crops. Thus, the returns estimated in Figure 1 from selling of surplus water are highly conservative. A detailed description of model assumptions and calculations to determine the extent of water sharing is in Appendix 1.

A third approach to improving the utilisation of solar pumps is for the farmer to sell surplus electricity to neighbours in a local mini-grid, or use it to power other productive activities. The benefit to the farmer compared with selling electricity to the distributor will depend on the local price of electricity, or the revenues from additional productive work. Given the seasonality of irrigation demand (see Figure 2), seasonal productive uses of electricity, such as post-harvest processing, are contenders to improve asset utilisation and add greater value for the farmer.

Figure 2: Surplus energy from solar pumps is well-suited for seasonal applications



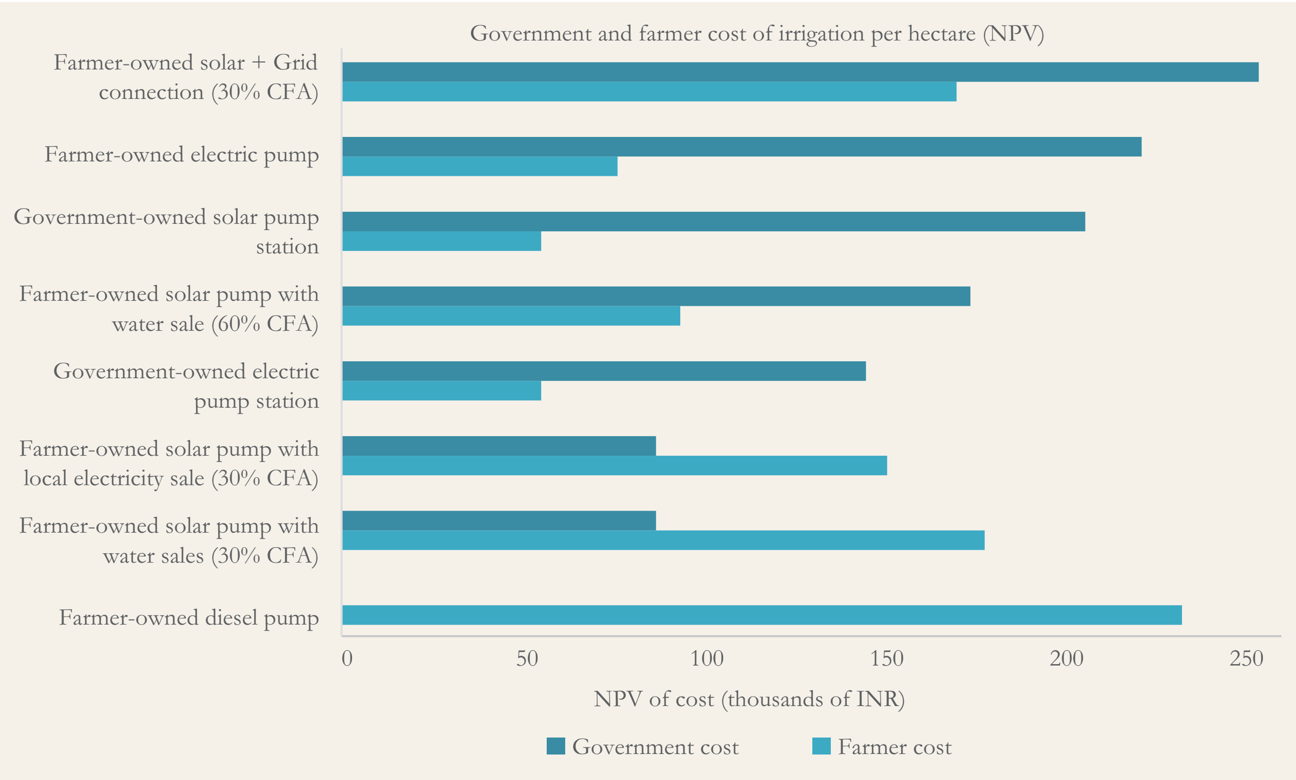
Source: Solar radiation values for Lucknow, UP, obtained from NREL: http://pvwatts.nrel.gov; Authors' Analysis

Seasonal non-irrigation applications include dal mills (gram); parboiling unit, puffing machine (rice); multipurpose grain mill, pedal-cum-power operated cleaner (wheat). Obtained from ICAR's AICRP on PHET report released in 2015. Non-irrigation activities calendar obtained from Crop Calendar of NFSM Crops.

3.1.5 How different irrigation options stack for the government

While promoting solar for irrigation, policymakers must consider government spending, farmers' affordability as well as economic viability of deployments to ensure that financiers back such deployments, and should seek strategies that take care of interests of all parties. Under the current subsidy rates, the government's cost to subsidise grid connections and electricity is high, but there are alternative approaches that benefit both the government and farmers (see Figure 3). Although financiers are not explicitly modelled, they would be interested in a farmer's economic outcome to ensure loan repayment. We have assumed that the government pays 90 per cent of the cost of a new grid connection and provides a feed-in tariff of INR 3.5 per kWh for electricity sold back to the grid. Further, based on the data from the electricity distribution companies of Uttar Pradesh, we assume that the prevailing farm electricity tariff recovers only 25 per cent of the cost of service to provide electricity to electric pumps (Rs 6.34 per kWh), due to aggregate technical and commercial losses (Uttar Pradesh Electricity Regulatory Commission, 2016).

Figure 3: Comparing farmer and government per-hectare cost across pumping options



Source: Authors' Analysis

3.1.6 Grid-connected solar pumps are not economically viable

We find that **grid-connected solar pumps are the costliest option for the government to provide irrigation to the farmers among the considered approaches, while not being the least cost option for the farmer.** High cost to the government is mainly because of subsidised grid extension, subsidy on solar pump and payments for surplus energy at feed-in tariff. The analysis is a conservative estimate of government costs as it does not include the cost of metering, monitoring and administration.

In circumstances such as a robust local water market where the farmer can sell many irrigation days per year, or flexible local electricity demand that can accommodate seasonal variations in the available surplus energy, the farmer can significantly improve his economic outlook by selling water or electricity. In general, our analysis suggests that **both the government and farmers would benefit from a higher capital subsidy, with local sale of water or electricity if possible, rather than connecting solar pumps to the grid.** Selling or utilising energy locally is a more attractive option. In the scenario of selling surplus energy locally, we assume only half of the available surplus energy being sold at INR 8 per kWh, a fairly conservative estimate. A greater local seasonal demand could only improve the economic viability of such a model.

3.1.7 Supporting stand-alone solar is economically attractive than subsidising new grid connections

We find that **even a 60 per cent capital subsidy for stand-alone solar pumps costs the government lesser than supporting subsidised electric pumps, particularly in regions with high electricity subsidy.** However, **farmers already having an electric connection or likely to get an electric connection soon, may not be interested in adopting solar even with such high subsidy**, as subsidised grid connection remains a cheaper option for them. However, **those farmers waiting for long for an electric connection or those who are unlikely to get an electric connection would find solar attractive at such a subsidy (or even less), as it is much more cost effective than owning a diesel pump or buying water/renting pump from the neighbourhood farmers.**

3.1.8 Centralised pumping stations

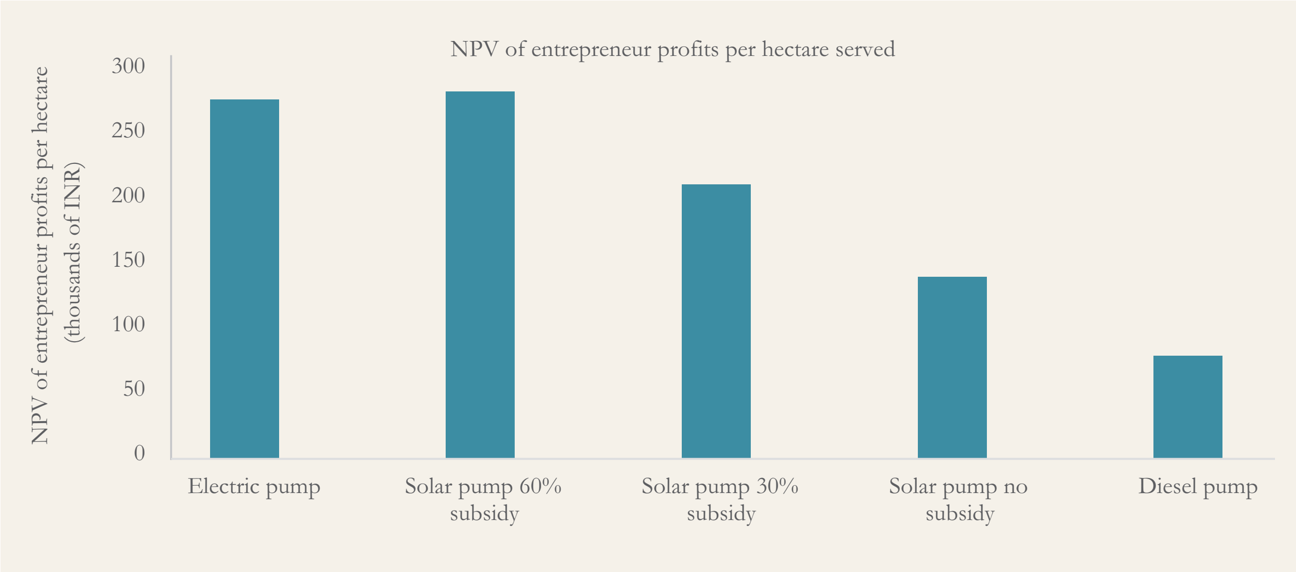
The cost of a government-owned centralised pumping station (solar or electric) depends on the water requirement and the number of connections. In the modelled scenario, the government's cost includes the per-hectare capital cost of a 7.5HP pump, solar panels and other electronic equipment. We neglect the cost to build and maintain infrastructure for water distribution (e.g., pipes or canals), so the model results underestimate the actual cost to the government. The government's cost of running an electric pump in centralised pumping stations is sensitive to the total irrigation demand (see Appendix B), but running a centralised pumping station with solar has a greater overall cost, under modelled assumptions. Higher cost of solar pumping stations as compared to electric ones is mainly on the back of smaller area that can be irrigated from solar pump of the same size as an electric pump, due to sharing constraint caused by limitation and variation in energy availability of the solar pump. Here, of course, the assumption is that electric pumping station is receiving reliable supply - not causing any such constraints in pump station operation - which is not usually the case in many parts of the country.

3.2 Water-as-a-service by entrepreneurs

In areas where there is a market for water, water-as-a-service from privately-owned solar pumps could be a viable business model. In the following analysis, we assume that an entrepreneur buys a 7.5HP irrigation pump for the purpose of selling water (i.e., she does not herself irrigate a farm, so all the revenue is from water sales to neighbouring farmers), and prices of water at a local market rate of INR 20 per kWh of pumping energy (see Figure 4). We modelled a 7.5HP pump at a well depth of 16m, average reported well-depth in Uttar Pradesh (Jain and Shahidi, 2018). Based on a conservative estimate of sharing, it could irrigate about four hectares for a modelled set of crops (rice and wheat).

If a reliable grid connection is available, an electric pump will generate the most profits for the entrepreneur, if she is able to secure a subsidised agricultural connection. This is due to very low electricity rates for agricultural customers (modelled as INR 100 per installed HP per month), and a 90 per cent subsidy for the upfront grid connection. However, electric pumps are relatively inexpensive to own and operate, so in areas where an agricultural connection is easily available, individual farmers might choose to buy their own rather than procuring water from an entrepreneur, unless the boring depth and hence, the bore-well cost is a significant barrier.

Figure 4: High utilisation under water-as-a-service model makes solar more attractive than diesel

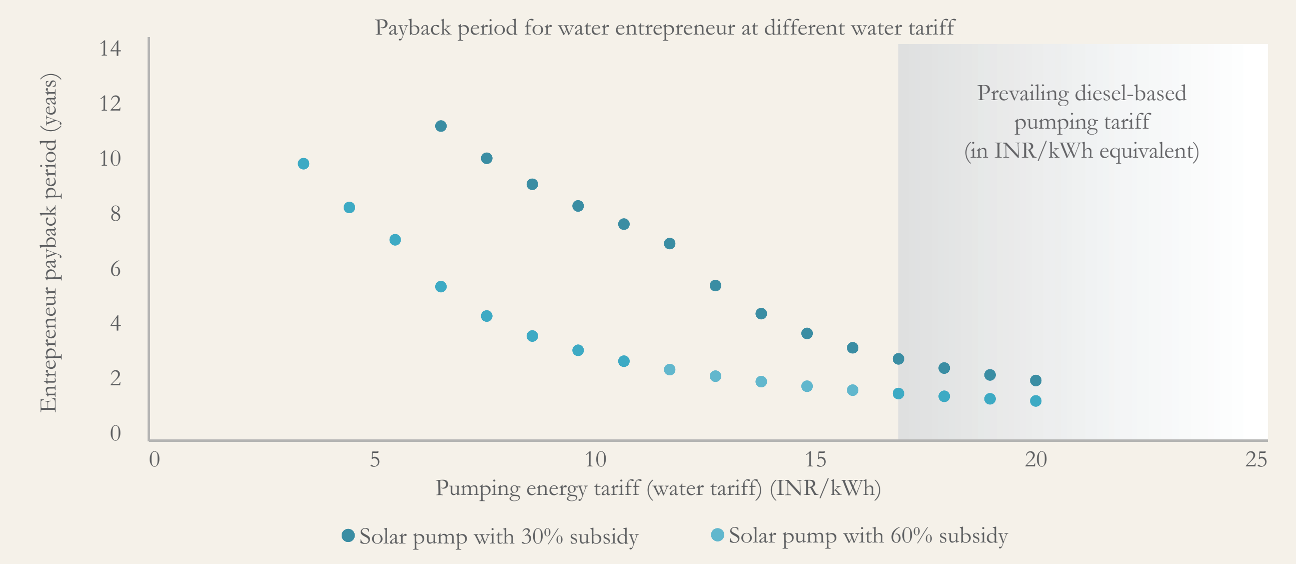


Source: Authors' Analysis

In an off-grid context, however, diesel and solar would be the only options for such an entrepreneur. The upfront cost of a solar pump may be a barrier to both entrepreneurs and farmers, but the life cycle cost of solar is lower. In the modelled scenario, a 7.5HP pump can irrigate almost eight marginal farms. As irrigation is seasonal, the surplus solar energy available during times of low water demand could provide an additional source of revenue from running complementary loads, particularly post-harvesting activities. This income is not included in the modelled profits.

In areas where diesel pumps are already in use, solar pump entrepreneurs could penetrate the market, and possibly displace the sale of water from diesel pumps by charging lesser than the prevailing tariff for diesel pumps. While the prevailing tariff is of the order of INR 20 per kWh equivalent of pumping energy, the minimum break-even water tariff for an 8HP diesel pump over a seven-year operating period is INR 17 per kWh. An entrepreneur charging the same tariff for water from a 7.5HP solar pump, with a 30 per cent capital subsidy, could expect a payback period of under three years (see Figure 5).

Figure 5: With 30 per cent capital subsidy, a solar entrepreneur could undercut tariff of a diesel pump operator and expect a payback period of under three years

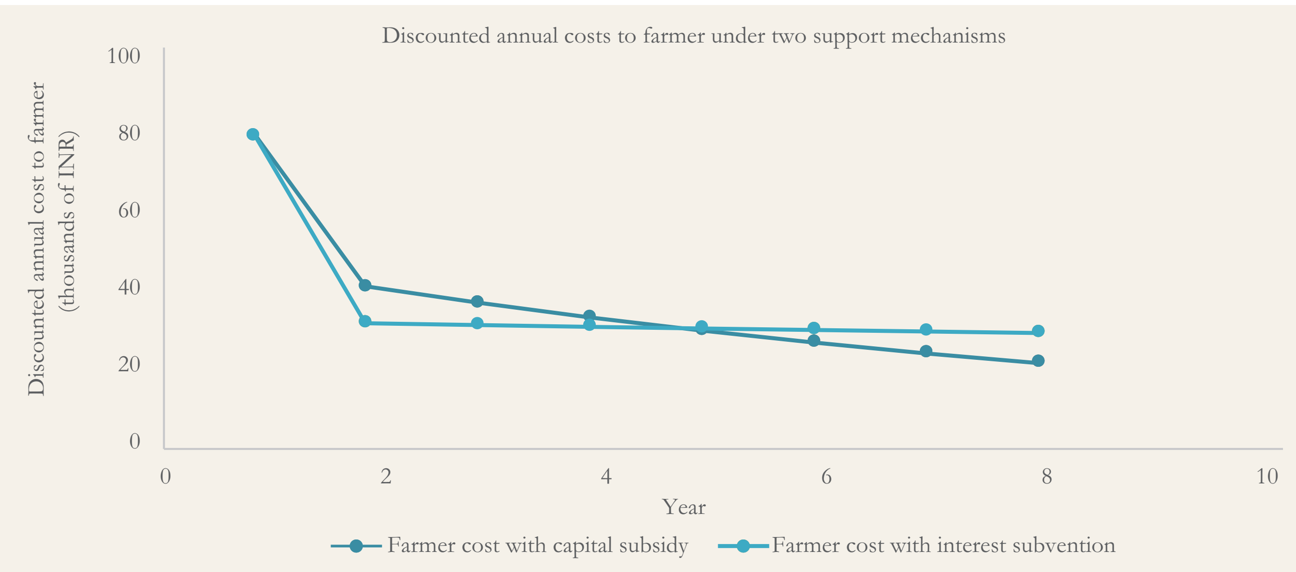


Source: Authors' Analysis

3.2.1 Supporting solar pumps through interest rate subvention

At the current solar pump prices, a government subsidy is required to make them an attractive pumping option for farmers. Subsidising the 100,000 solar pumps per year proposed by MNRE, however, will require an enormous annual outlay of government money. For example, if each subsidised pump is 2HP and the government provides CFA of 25 per cent, the annual cost to the Central government alone will be almost INR 5 billion. An alternative mechanism through which the government could subsidise solar irrigation pumps is to provide an interest rate subsidy, or interest subvention. This would spread the government's expenditures over the duration of the farmer's loan. This scheme could also benefit the farmer, whose near-term real and discounted annual costs will be lower with interest subvention than under the capital subsidy scenario. In Figure 6, solar pumps are subsidised either with a 26.5 per cent capital subsidy, or with full interest rate subvention for a seven-year loan with a 10 per cent interest.

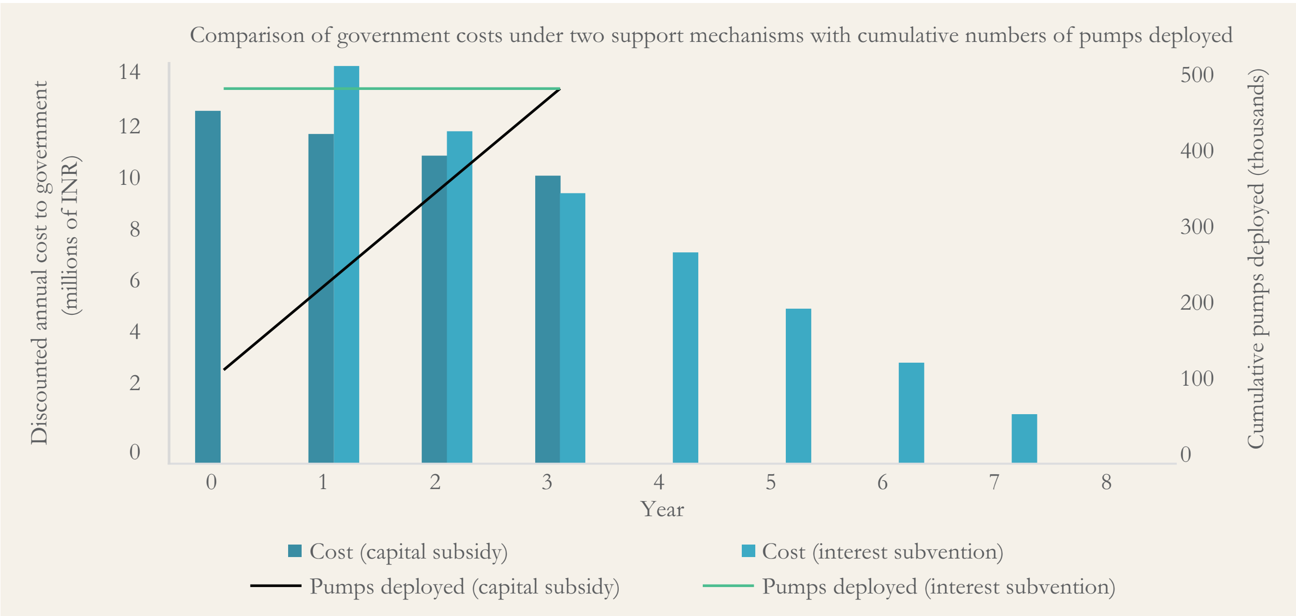
Figure 6: Interest rate subvention decreases annual cost for farmer in earlier years compared to equivalent capital subsidy support



Source: Authors' Analysis

The benefit of interest subvention is that without changing the total support provided to farmers, the government could subsidise more pumps in year one, but bear the expense over the length of the farmer's loan. Figure 7 shows the discounted annual cost to the government to subsidise 400,000 solar pumps. In the case of interest subvention, all the pumps are purchased by farmers in year one, whereas under the capital subsidy scheme, 100,000 pumps are deployed each year for four years. The 26.5 per cent subsidy rate provides the same total support to the farmer as full subsidy of 10 per cent interest on a loan of INR 212,349 over seven years (assuming 3HP pumps). In both cases, the farmer pays 20 per cent of the system cost as a down payment. The cost to the government under interest subvention is INR 105,000 per farmer, as opposed to INR 89,000 under the capital subsidy. Researchers in the past have also advocated an interest rate subsidy over capital subsidy on the grounds of relative performance and administration of both, under the erstwhile MNRE schemes for other technologies, such as solar water heaters (Chandrasekar and Kandpal, 2005). However, while implementing such a scheme, it would be important to first understand the farmers' preferences among the two approaches and accordingly, awareness drives could be planned to engage and persuade farmers about the economic as well as the larger social benefit of such an approach.

Figure 7: Government could increase the pace of solar pump deployment under interest subvention without incurring high upfront costs



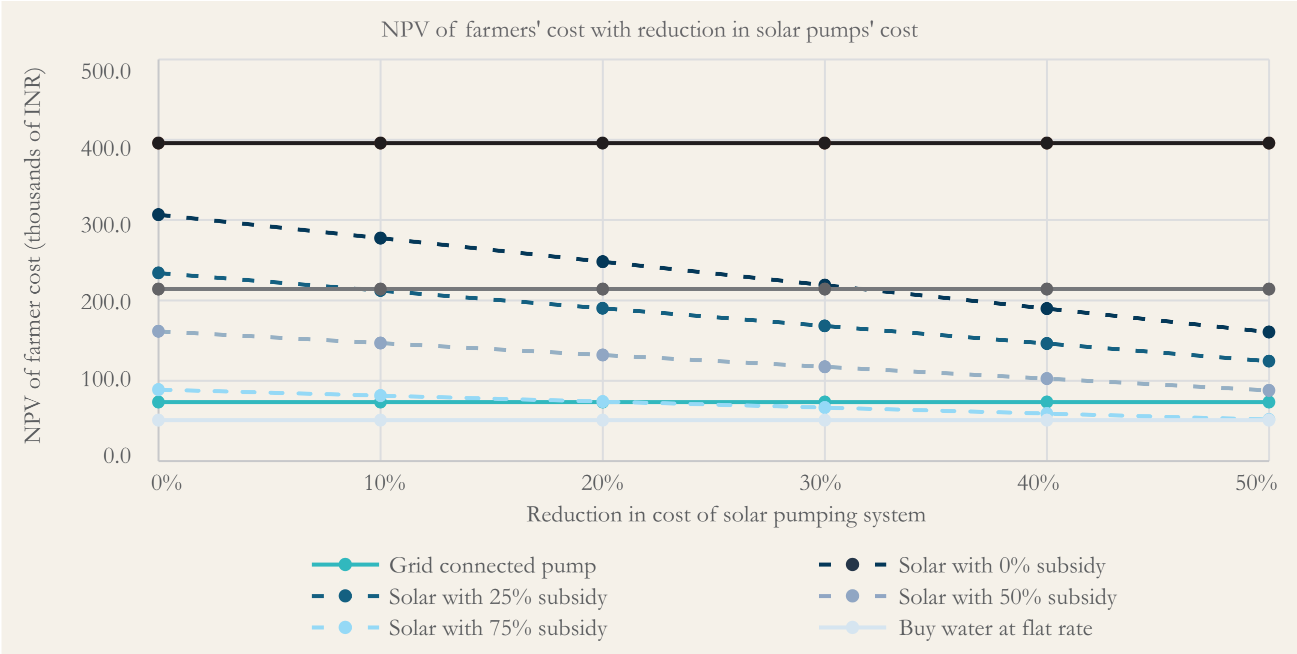
Source: Authors' Analysis

3.3 Investment sensitivity to reductions in capital costs

Decreasing costs are cited as a key to the future viability of solar (KPMG, 2014). Electric pumps will remain the lowest-cost option for farmer-owned pumps unless the government reduces subsidies for grid electricity. In this analysis, we assume a decrease in the total cost of the solar pumping system, which includes pumps, solar panels and related electronic equipment. Electric and diesel pumps are mature technologies and their costs are held constant.

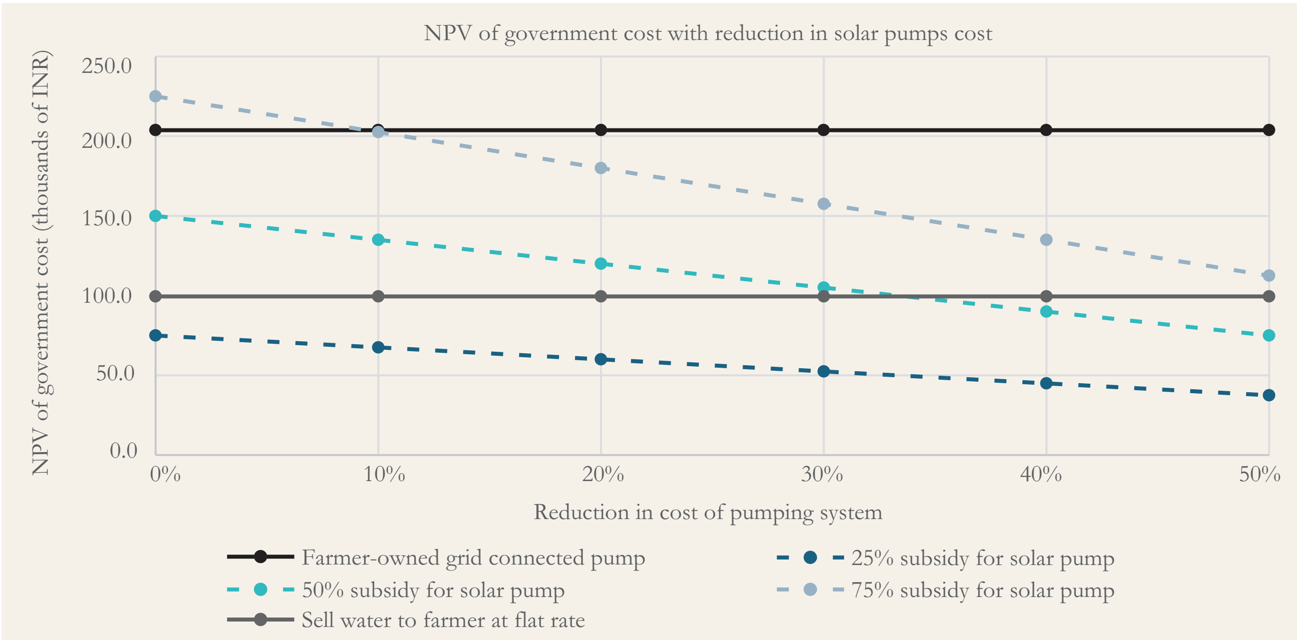
From the government's perspective, farmer-owned solar pumps are preferable to electric pumps under current prices, unless subsidy rates for solar exceed 80 per cent (see Figure 9). As the cost of solar panels declines, the case for shifting government subsidies from grid connections to solar, as proposed by Agrawal and Jain (2015), becomes more attractive. If costs decrease by 20 per cent, for example, the government could provide 60 per cent CFA for solar pumps and spend INR 40,000 less per farmer for a 3HP pump.

Figure 8: Decreasing pump and panel costs could change farmer's preference between solar and diesel pumps



Source: Authors' Analysis

Figure 9: Under modest reductions in pump and panel prices, the government could provide generous subsidies for solar pumps at a lower cost than supporting electric pumps

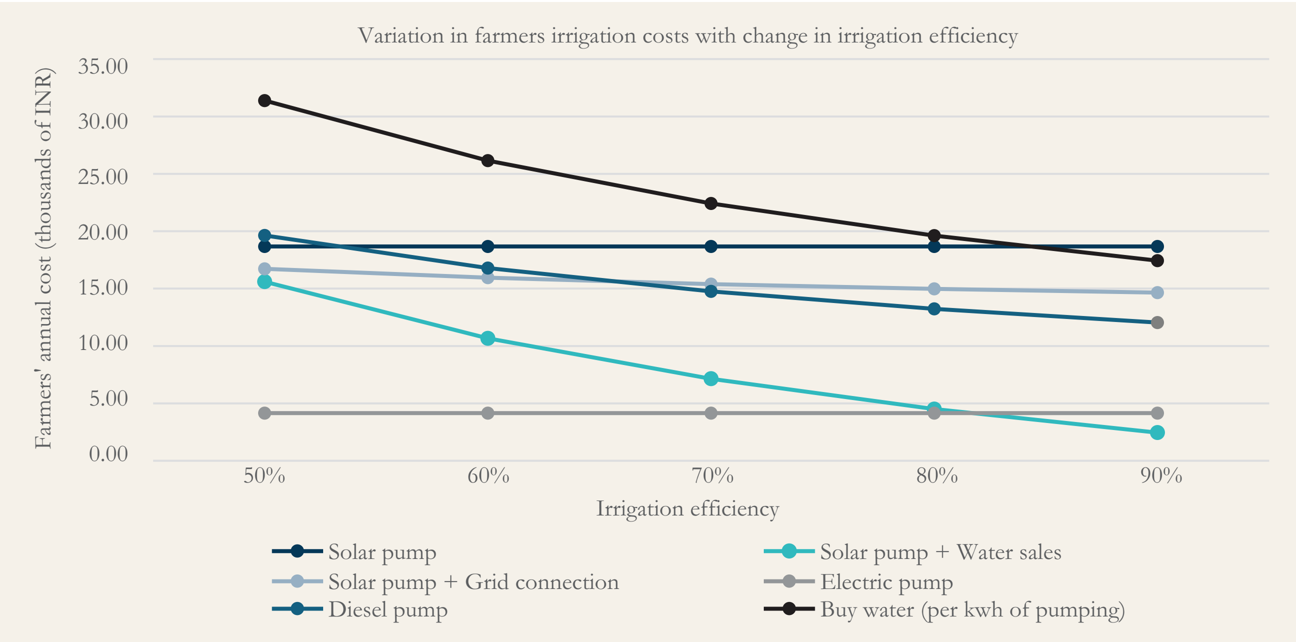


Source: Authors' Analysis

3.4 Role of irrigation efficiency on farmer's economics

The economics of solar pumps, in contrast to diesel or electric pumps, are dictated by the purchase price. Once the pump is installed, the marginal cost of pumping is zero, so changing between a more or less efficient means of irrigation using the same pump size will not directly affect operating costs, though it may impact revenues. If irrigation efficiency decreases, farmers who sell water or electricity will have fewer surplus pumping days or units of electricity to sell, as they will need to use the pump more for themselves (see Figure 10).

Figure 10: Farmers who sell water or electricity locally from solar pump can improve their economic outlook by improving irrigation efficiency



Source: Authors' Analysis

3.5 Groundwater depletion

A serious concern with solar pumping in India is that there is little incentive for the owners of solar pumps to irrigate efficiently and excessive water use leads to groundwater depletion. If a farmer can make money selling surplus energy to the grid, or extra water to neighbours, this effectively puts a price on water (Fishman *et al*. 2015). A farmer's revenues from selling surplus water are highly sensitive to irrigation efficiency, as shown in Figure 10. So, **encouraging pump sharing may be an opportunity for the government to increase the utilisation of solar pumps as well as the impact of government support, while creating a market-based solution to ensure efficient and judicious use of the groundwater.**

4. Policy Recommendations

Solar pumps hold the promise of improving access to irrigation in India using renewable energy, but despite the government's support and establishment of schemes to promote solar pumps, the pace of adoption has lagged behind targets and expectations. Given the potential benefits of solar pumps, alternative approaches to promote their adoption should be considered so that the government support can be allocated effectively. In this study, we developed a robust economic model of irrigation pumps and used it to assess different deployment scenarios that we believe are of interest to policymakers. Key policy recommendations based on our research are highlighted below:

- For farmers whose crops require only intermittent and very limited pump use, diesel pumps may be more economical than solar pumps. **Individual ownership model of solar pumps should target farmers planning greater numbers of cropping cycles, or having more irrigation days each year**, as they would find solar pumps economically attractive compared to diesel, even without subsidy.
- **Individually owned solar pump deployment should focus on farmers currently deprived of grid connections.** A farmer receiving reliable subsidised electricity from the grid would not find a stand-alone solar pump attractive even at 60 per cent capital subsidy.
- **Farmers awaiting an electric connection for long or those who are unlikely to get an electric connection may find solar attractive at even 30 per cent subsidy, provided affordable financing is available**, as it is much more cost effective than owning a diesel pump or buying water/renting pump from neighbourhood farmers.
- **Connecting solar pumps to the grid may provide some additional revenue to solar pump owners; however, they would prefer selling water using surplus energy, should there be a local demand.** Equivalent tariff for such pumping service is INR 20 per kWh, which is much higher than the feasible feed-in tariff. Thus, the government investment on extending the grid to solar-pump may not lead to an adequate return in all circumstances. Moreover, **high cost to the government to subsidise the solar pump, grid connection and feed-in tariff makes grid-connected solar pumps economically unattractive for the government**.
- **Providing interest-free loans to farmers with reduced capital subsidy could potentially facilitate the deployment of a much larger number of solar pumps in a shorter span of time, while spreading the government cost over the term of the loan.** Such an approach could also be more attractive for farmers, given their lower cash outlay in earlier years. Implementation of an interest-rate subsidy will require long-term commitment from the government and financiers, as well as an effective coordination between them to ensure a sustainable strategy for both. It may also ask for significant engagement of farmers to opt for such an approach.
- **Water-as-a-service by village level entrepreneurs, including farmers with surplus pumping energy, is a promising model for improving the utilisation of solar pumps creating additional revenue, thus improving their economic viability and providing irrigation access to marginal farmers**. The viability of solar pump sharing, and the significance of the revenue from it would remain sensitive to the timing of local irrigation needs. **In areas with a dominance of diesel pumps for renting or selling water, solar-based water-as-a-service model could have a payback of two to four years.**
- Encouraging pump sharing could be an opportunity for the government to increase the utilisation of solar pumps as well as the impact of government support, while creating a market-based solution to ensure efficient and judicious use of the groundwater.

5. Discussion

While solar pumps are advantageous for farmers and the government under the modelled assumptions, their attractiveness when compared with electric or diesel pumps is determined by factors such as the number of days the pump is used each year, the price of diesel fuel and the access to grid electricity or water infrastructure. Policies to promote solar pump deployment must, therefore, take variations in these factors into account so that the government support for solar pumps can be targeted towards areas where economic outcomes are favourable to both farmers and the government. For example, our analysis has shown that although grid-connected solar pumps enable farmers to earn additional revenue from feed-in tariffs, this deployment model is the costliest approach for the government per unit area of irrigated land. Instead, in areas where there is a market for water, farmers can earn the same revenue from selling water to neighbouring farms from a subsidised solar pump, not only reducing the government cost, but also improving the impact of the government subsidy in terms of the area irrigated from a pump. Similarly, farmers who require a high flow rate of water, but only sporadic use (e.g., for backup if there is an unreliable primary irrigation source), would be better off with a diesel pump than with solar.

The economic model developed for this work provides an additional perspective on where solar pumps should not only be deployed, but how they could be supported in a way that is both economically preferable for the farmer and makes a good use of the government spending. Financiers, though not explicitly modelled here, also play an important role in the development of an effective and sustainable strategy to promote solar pumps, as given the high upfront cost of solar pumps, their provision of equity for farmers is a necessary component of pump ownership. Financiers will only be willing to provide capital for investments that are likely to yield profits for the farmer.

Our model provides insights into the economic viability of solar pumps across different conditions in India, but will be most valuable when tailored to a state or region to aid in the formation of an effective subsidy policy for that state. Tools such as the economic model developed here and the CEEW's Decision-Support SPIS tool can be helpful guides for identifying regions and farmers for whom solar pumps are the best option. However, these tools can only provide one perspective, and their results must be augmented by an understanding of the farmers' and financiers' preferences, and local factors not accounted for in this study. Researchers and different levels of government should work together to identify suitable approaches to solarise irrigation, while maximising the socio-economic impact of the government spending.

Finally, the government should continue to support solar pumps in the country, but should do so in a manner that seeks not to attain a set number of deployed irrigation pumps each year, but rather to promote deployment scenarios that are suitable to the given context. Only then, we would be able to effectively harness the potential of a decentralised technology, to maximise the socio-economic impact and minimise the potentially harmful environmental impacts.

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Appendix 1: Model calculations

Pump sizing

Pump size is an endogenous variable that depends on the flow rate required to meet irrigation needs. The flow rate is estimated as the maximum flow needed to meet the water demand of a crop within a given time period, which is in turn determined by the number and duration of irrigation periods in a crop's growing cycle. For example, wheat requires 550mm of water over its growing season and is generally irrigated at six stages of crop growth (Kumar, 2010). The criticality and length of these stages vary, but we assumed that at each stage, the water requirement must be met within a fix-day period. With the simplifying assumption that each irrigation cycle requires the same amount of water, and using, for example, a one-hectare farm and six hours of pumping per day, this yields the following:

$$\text{Pump flow rate} = \frac{(550\text{mm})(1\text{ hectare})}{(6\text{ cycles})\left(\frac{5\text{ days}}{\text{cycle}}\right)}\left(\frac{10{,}000\text{m}\,\text{m}^2}{\text{hectare}}\right)\left(\frac{1\text{m}}{1000\text{mm}}\right)\left(\frac{1\text{ day}}{6\text{ hours}}\right) = 30.6\,\frac{\text{m}^3}{\text{hour}} \qquad (1)$$

With the assumed efficiencies and a well depth of 16m, a 3.5HP pump would be required to meet this flow rate requirement. We note that this is a conservative estimate and that a smaller pump could meet the total annual *volume* of irrigation water required, but not this time window constraint.

Constraints on sale of water or sharing of pumps

The number of farmers or the amount of land that can be served by one pump depends on one of the two constraints: The first is the timing of irrigation. If farmers in the same area grow the same crops, their critical irrigation requirements will occur at approximately the same time. A model input is the number of days of variation over which crops are assumed to be planted, i.e., the span of time over which farmers in one area will plant the same crop (the default is seven days, to which is added the length of the shortest irrigation window, in this case three days). Based on the chosen pump size, we find the minimum number of days to meet the highest crop irrigation requirement. This is the amount of time needed by the farmer himself, and the remaining days in the cropping window are then available. Dividing those remaining days by the total number of irrigation days required by the farmer in one year yields the fraction of additional, similar farmers that can be irrigated by the same pump.

The second constraint is applicable only to solar pumps and accounts for the energy generated and required at different times of the year. Using seasonal crop water requirements and monthly solar radiation data, the energy generated and required for pumping may be determined. A farmer with a solar pump can only sell water if there is an energy surplus. As in the irrigation timing case, the number of additional farmers who can rely on the same pump for irrigation is found by dividing the minimum monthly surplus irrigation days by the farmer's annual irrigation days. Table 2 shows an example of a farmer, with one hectare of land and a 7.5HP pump, who can provide irrigation to 1.8 extra farms every year. In this scenario, the kharif (June-September) crop is rice, which has a higher water requirement and low irrigation efficiency due to flood irrigation. The number of days available for sale is constrained in the model so that the energy required for pumping in one month is never negative.

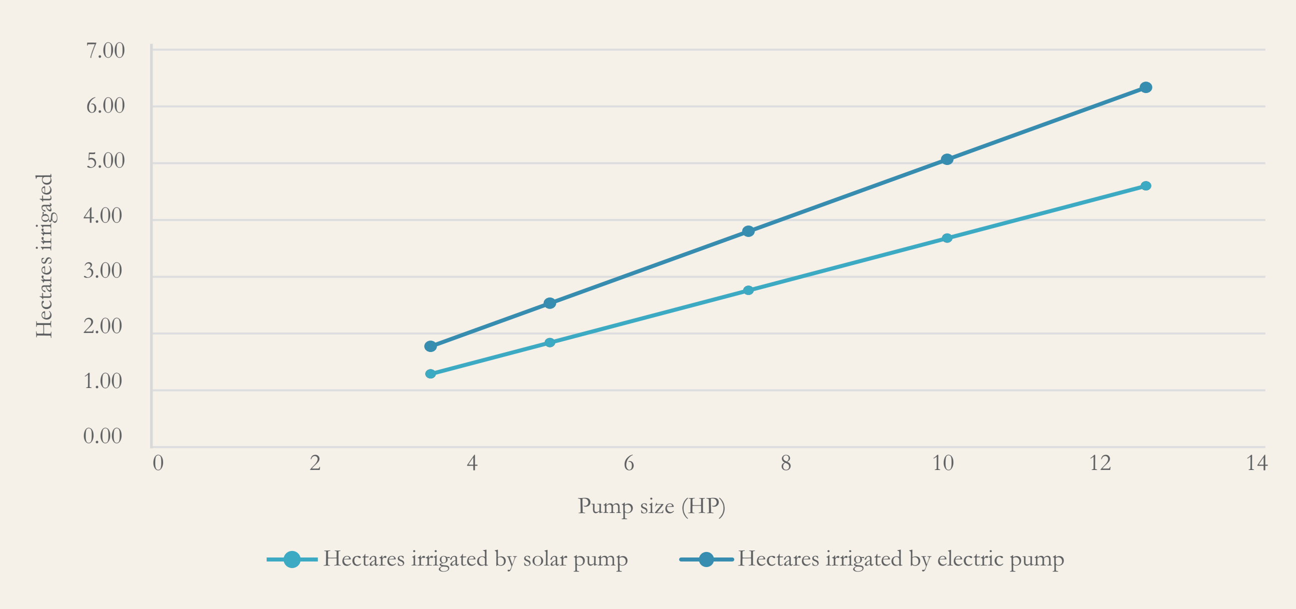
Table 2: Energy generated by photovoltaics and required for pumping

Month	Radiation for selected state (kWh/m2/day)	Energy generated (kWh)	Energy for farmer irrigation (kWh)	Farmer monthly surplus (kWh)	Energy for sale of water (kWh)	Total energy used for irrigation (kWh)	Surplus (kWh)
January	3.9	684	119	565	209	327	356
February	5.3	835	119	717	209	327	508
March	6.5	1,128	171	957	301	472	656
April	6.9	1,157	171	986	301	472	684
May	6.2	1,071	171	900	301	472	599
June	5.3	896	307	589	541	848	48
July	4.9	851	307	544	541	848	3
August	5.1	887	307	580	541	848	39
September	5.1	848	307	541	541	848	0
October	5.6	977	119	859	209	327	650
November	4.6	777	119	659	209	327	450
December	4.1	708	119	589	209	327	381
Yearly	63.6	10,819	2,336	8,484	4,111	6,446	4,373

Source: Authors' Analysis

When a solar pump is installed, the model uses the smaller of the two constraints described above (irrigation window or available solar energy). For diesel and electric pumps, only the former constraint applies. For the reference scenario, radiation, rainfall and crops for this report, the constraint for solar was always smaller than that for electric or diesel. Therefore, as shown in Figure 11, an electric pump may be able to irrigate larger farms, or more number of farmers. We again note that this is a conservative estimate, as it assumes that farmers in a given area plant the same crops at about the same time. Farmers wishing to either sell more water, or water buyers seeking available pumps, could choose to plant different crops, or vary their planting days more widely, and in doing so shift their irrigation requirements to the months where the surplus (see the last column of Table 2) is greater. Finally, productive activities other than irrigation, such as food processing, could be an additional source of revenue for farmers during months of energy surplus.

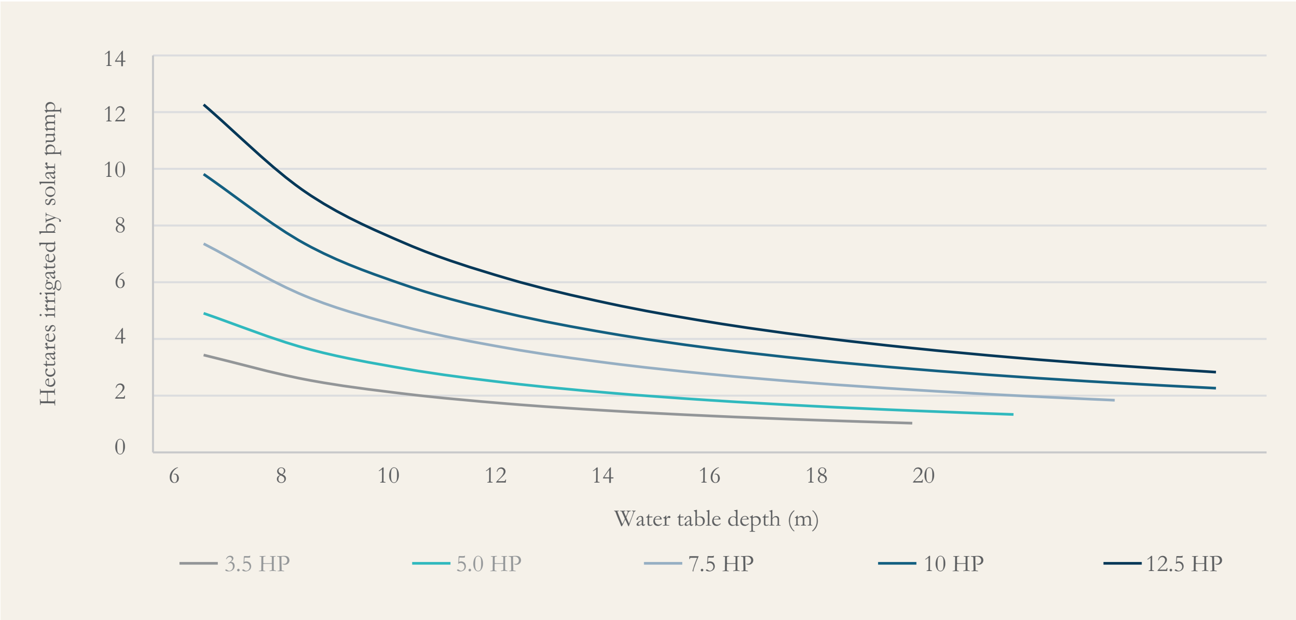
Figure 11: Solar pumps are constrained by available radiation during seasons of high water demand, so may be able to support fewer farmers year-round



Source: Authors' Analysis

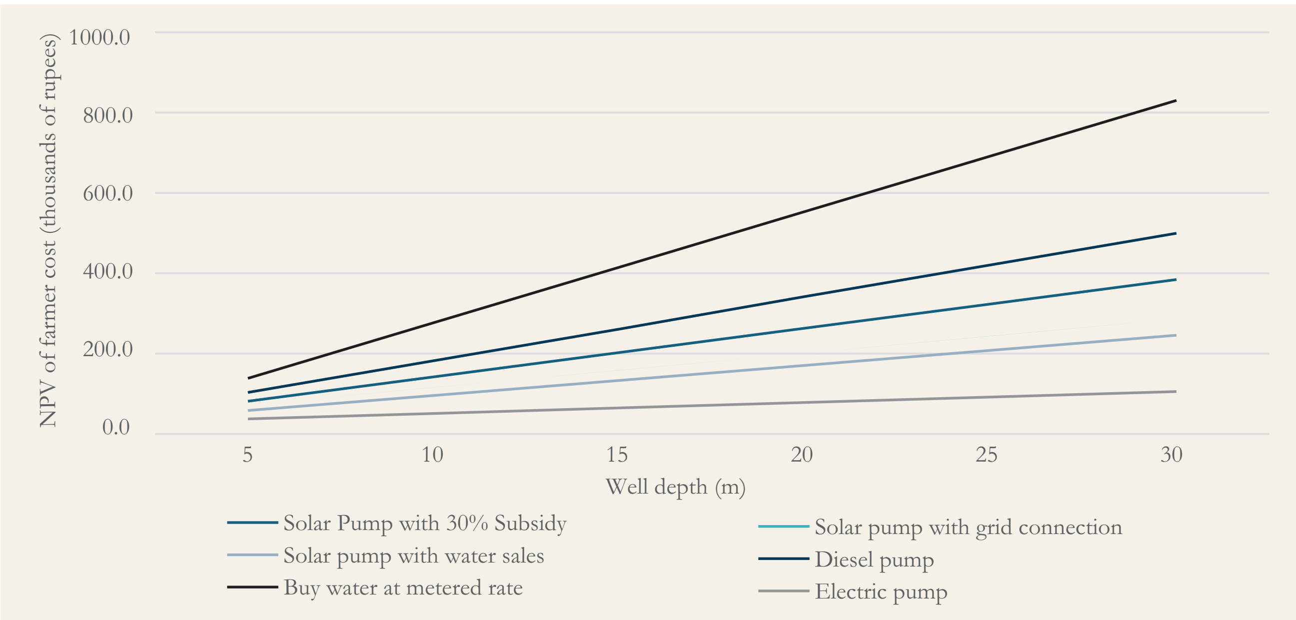
Appendix 2: Sensitivity analysis

Figure 12: Pump flow rate is sensitive to well depth. Shallower wells and higher flow rates enable greater sharing of solar pumps



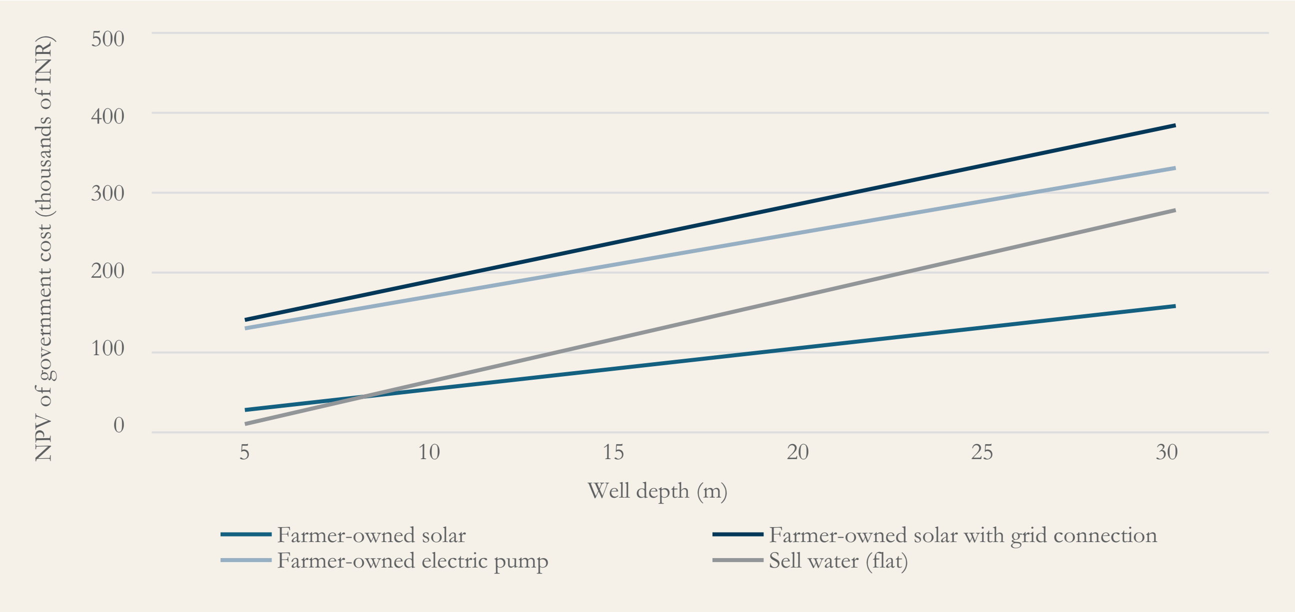
Source: Authors' Analysis

Figure 13: NPV of farmer cost to irrigate vs. well depth



Source: Authors' Analysis

Figure 14: NPV of government cost to subsidise farmer-owned pumps or sell water from an electric pump vs. water table depth (30% subsidy for farmer-owned solar pumps)



Source: Authors' Analysis

Appendix 3: Model inputs for reference scenario

Operating parameters and costs

Parameter	Value	Units	Notes
Location	Uttar Pradesh		Determines solar radiation and rainfall data
Size of farm	1	hectares	
Irrigation hours per day	6	hours	Must be < daylight hours if stand-alone solar
Operating period for system	15	years	
Water table depth	16	m	Determined by location. data from Central Groundwater Board: cgwb.gov.in.
Height of discharge above well	0	m	Summed with water table depth to get total head. Can use to account for horizontal pipes as well if have friction factor.
Local crop planting time window (min)	7	days	
Irrigation efficiency of rainfall	80%		Estimate of how much rainfall is used by crops - applied across all growing seasons
Crops	Season	Primary crop	Irrigation efficiency estimates: 50% for canals, 70% sprinklers, 90% drip
	Kharif	Rice	50%
	Rabi	Wheat	70%
	Summer	Gram	70%
Electric pump lifetime	10	years	Model includes cost to replace pump after lifetime
Mechanical efficiency of electric pump	45%		Depends on pump quality (using Shakti pumps as references)
Electric motor efficiency	80%		
PV panel lifetime	20	years	
DC system efficiency	80%		Estimate from NREL (http://pvwatts.nrel.gov)
Inverter efficiency	95%		Estimate from NREL
Size of government-owned pump	7.5	HP	Used to estimate cost to government for water provision
PV panel price	60,000	Rs/kWp	
Cost of PV electronics as fraction of pump + panel costs	30%		
Additional cost for DC pump	10%		Fraction of AC pump cost
Grid connection total cost	100,000	Rs	Split between farmer and government
Grid connection paid by farmer	10,000	Rs	
Cost of grid connection (government portion)	90,000	Rs	Baseline: government pays 90% of connection cost
Drilling well	0	Rs	Have modelled all scenarios as though well already exists

Parameter	Value	Units	Notes
PV system maintenance (panels + pump)	2,000	Rs/year	
Electric pump maintenance (no PV)	1,000	Rs/year	
Feed-in tariff (metered)	3.5	Rs/kWh	Constant
Cost of service for electric distributor	6.34	Rs/kWh	(4% CAGR) includes electricity procurement and O&M (CEEW analysis on UPERC data)
Local pumping tariff	20	Rs/kWh	(4% CAGR) from Bihar survey (GIZ), INR 100-120 /hr for 3-5HP pumps. For a 4HP pump at INR 110/hr, get INR 29.48 /kWh for rental
Local electricity selling price (mini grid)	8	Rs/kWh	(4% CAGR) depends on local market.
Cost of water for irrigation from government	500	Rs/month	(4% CAGR) flat rate, estimated from CEEW survey
Grid electricity (metered)	2	Rs/kWh	(4% CAGR) state-wise average rate of electricity for domestic and industrial consumers at data.gov.in
Grid electricity (flat rate for agricultural use)	100	Rs/HP/ month	(4% CAGR) model assumes a flat rate if no solar panels, rate estimated from CEEW analysis
% of cost of service recovered by government	25%		For flat rate agricultural connections
Loan interest rate	10%		
Required rate of return for farmer equity	15%		
Loan term	7	years	
Corporate tax rate	0%		Farmers not taxed
Government discount rate	7%		Securities
Lifetime of diesel pump	7	years	
Maintenance cost of diesel system	3,000	s/year	
Max head for diesel pump	16	m	Assume diesel pumps are surface pumps
Diesel pump efficiency	40%		
Diesel motor efficiency	33%		
Energy density of diesel fuel	45.8	mJ/kg	
Density of diesel	836	kg/m^3	
Energy content of diesel	38,289	kJ/L	
Price of diesel	56	Rs/L	(4% CAGR)

Source: Authors' Analysis

Crop water requirements

Crop	Water requirement in one season (mm)	Number of irrigation cycles per season	Length of shortest irrigation window (days)	Water in each irrigation (mm)
Gram	450			
Groundnut	600			
No crop	0			
Ragi (millet)	425			
Rice	1250	30	3	416.7
Sorghum	550			
Soybean	600			
Wheat	550	6	5	916.7

Data source: http://agropedia.iitk.ac.in/content/water-requirement-different-crops; Authors' Analysis


Image: Daniel Burka/Unsplash

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