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Outcome Evaluation of Climate-Smart Research on Solar-Powered Irrigation in India

Simulation Modeling

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Acronyms

CCAFS – CGIAR Research Program on Climate Change, Agriculture and Food Security
DISCOMs – Electricity distribution companies
GHG – Greenhouse gas
hp – Horsepower
ITP – IWMI-Tata Water Policy Research Program
IWMI – International Water Management Institute
KUSUM – Kisan Urja Shakti evam Utthan Mahabhiyan
NGO – Not-for-profit organization
ROI – Return on investment
SIP – Stochastic information package
SPaRC – Solar power as a remunerative crop

Glossary of terms

Decision analysis – Decision analysis is a normative method for selecting among actions that have uncertain outcomes. This outcome uncertainty can be characterized by probability distributions for variables that represent the key consequences of the considered actions.
Monte Carlo simulation – Monte Carlo simulation performs risk analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty. It then calculates results repeatedly, each time using a different set of random values from the probability functions.
SIPmath™ – An open standard that codifies the storage of an uncertainty as a stochastic information packet (SIP), an unambiguous data array with provenance.
Solar power as a remunerative crop (SPaRC) – Approaches by which farmers are able to earn money by selling solar power back to the grid.
Stochastic – Having a probability distribution or random pattern that may be analyzed statistically but may not be predicted precisely.
Stochastic information packet (SIP) – An array of possible outcomes of some uncertainty.
Stochastic simulation modeling – Simulation modeling that includes uncertainty.

Summary

As part of an Outcome Evaluation of Climate-Smart Research on Solar-Powered Irrigation in India, a simulation model was constructed with the objective of developing a scenario-building model of the main factors influencing adoption, major costs, benefits and risks associated with solar-powered irrigation. The main focus of the evaluation was on the solar power as a remunerative crop (SPaRC) model, also known as KUSUM-C under the multibillion-dollar Kisan Urja Shakti evam Utthan Mahabhiyan (KUSUM) initiative of the Government of India. The main objectives of the simulation modeling component were to: (i) project income and environmental benefits of the SPaRC scheme over the next 20 years; (ii) identify variables to which benefits are particularly sensitive; (iii) run scenario analysis for different values of sensitive variables; (iv) pinpoint what further research or actions could help to enhance adoption and outcomes, and what variables should be closely monitored; and (v) provide a learning tool that can be used to compare what actually happens with projections over time and can be continuously updated.

A decision analysis approach is taken, which is designed to cope with improving decisions under conditions of large uncertainty and limited data. The analysis is a probabilistic risk-return approach that quantifies the current state of uncertainty, including the costs, benefits and risks associated with a proposed intervention. The model is used to help answer evaluation questions tackled in the main report. All variables in the model are represented as probability distributions to reflect the current state of uncertainty in knowledge. The distributions are constructed based on data from available literature and reports, where available, and through elicitation from subject matter experts. Monte Carlo simulation is used to propagate the uncertainties through to the outcome variables. Different policy-relevant scenarios were simulated by changing the input values of key variables. A dashboard is provided that allows users to interactively change values and view the effect on outcomes.

Simulations of incremental benefits to 2040, compared with non-solar alternatives, are made for KUSUM-C and a competitor model, KUSUM-A, which provides farmers with direct power for irrigation from substation-level solar power plants. The simulations are made for Gujarat State only in this report, but the model can be parameterized with input data for other states.

Using the baseline assumptions, by 2040, KUSUM-C increased discounted net income at farm level by USD 13,000 (expected value) with a chance of income loss at farm level of 5%. There are significant upside opportunities for high levels of farm income in KUSUM-C. At farm level, KUSUM-C reduced water use by 14,300 m^3/yr. The equivalent increase in farm net income in KUSUM-A was only USD 1,000 but with no chance of loss. Farm water use increased in KUSUM-A by 40,000 m^3/yr.

The baseline simulations project about 1 million farm households (expected value) will have adopted solar-powered irrigation by 2040, made up of 61% KUSUM-C and 39% KUSUM-A and 97% of these will have benefited from increased income. Electricity distribution companies (DISCOMs) plus local government are projected to generate a net discounted income of USD 1,000 million in KUSUM-C with a 27% chance of loss, compared with a loss of USD 60 million in KUSUM-A with a 67% chance of loss. At a project level, discounted benefits from reduction in greenhouse gas emissions were USD 1,030,000 million (expected value) in KUSUM-C compared with USD 310,000 million in KUSUM-A.

The results are sensitive to adoption rates, which are highly uncertain. The benefits of KUSUM-C are strongly dependent on maintaining subsidies and loans to farmers, maintaining tariff rates for sale of solar power back to the grid, and on strong local community and supporting organizations.

A number of priorities are identified for further research and monitoring, targeted at areas of greatest uncertainty and largest effect on outcomes. Recommendations are given for further application, maintenance and improvement of the model as a research and policy learning tool.

Introduction

The simulation modeling component is in support of the Outcome Evaluation of Climate-Smart Research on Solar-Powered Irrigation in India (see main report). The objective was to develop a scenario-building model of the main factors influencing adoption, major costs, benefits and risks associated with solar-powered irrigation, with a special focus on the solar power as a remunerative crop (SPaRC) model, also known as KUSUM-C under the multibillion-dollar Kisan Urja Shakti evam Utthan Mahabhiyan (KUSUM) initiative of the Government of India. The main objectives were to: (i) project income and environmental benefits of the SPaRC scheme over the next 20 years (evaluation question 5); (ii) identify variables to which benefits are particularly sensitive; (iii) run scenario analysis for different values of sensitive variables; (iv) help pinpoint what further research or actions could help to enhance adoption and outcomes, and what variables should be closely monitored; and (v) provide a learning tool that can be used to compare what actually happens with projections over time and can be continuously updated.

The overall modeling approach and main results are described in this report and the model details are described in the Excel model itself, available together with supporting publications at: https://www.dropbox.com/sh/4m989n35iybl817/AAD-bUbBrYve2ou75sgw6Dyla?dl=0.

Modeling approach

Overall approach

A decision analysis approach is taken, which is designed to cope with improving decisions under conditions of large uncertainty and limited data (Howard and Abbas 2015). The analysis is a probabilistic risk-return approach (Luedeling and Shepherd 2016) that quantifies the current state of uncertainty, including the costs, benefits and risks associated with a proposed intervention (Fenton and Neil 2018). The modeling approach (Table 1) is helpful in projecting potential impacts in relation to CGIAR intermediate and system-level outcomes. This decision analysis approach is designed to provide insights even in data-limited environments by taking a causal approach, representing uncertainty and incorporating expert knowledge (Fenton and Neil 2018). Sensitivity analysis is used to help identify what further research or actions could help to enhance adoption and outcomes, and what variables should be closely monitored. In this case, the model was built in Microsoft Excel using freely available tools. To improve the communication of results to researchers and stakeholders, a simulation dashboard was provided that allows interactive simulation of the influence of key policy parameters on outcomes.

Modeling tools

The model was built to help answer evaluation questions tackled in the main report. All variables in the model were represented as probability distributions to reflect the current state of uncertainty in knowledge. The distributions were constructed based on data from available literature and reports and through elicitation from subject matter experts as described by Luedeling and Shepherd (2016). Monte Carlo simulation was used to propagate the uncertainties through to the outcome variables. Different policy-relevant scenarios were simulated by changing the input values of key variables.

Table 1. Key steps in the simulation modeling approach. There was iteration among the steps.

Model building 1. Assemble background information on the intervention from literature and experts. 2. Define key decisions that the evaluation model may inform. 3. Specify the main model components and levels of disaggregation to be included, and the geographic scope. 4. Building on the scaling theory informed by ex-post work, assemble a causal model of the main factors influencing adoption, major costs, benefits and risks. 5. Program the model in Microsoft Excel. 6. Test and embellish the model through individual interviews of experts.
Data assembly 1. Define data needs and design a data entry template. 2. Identify key data sources and experts who can provide estimates. 3. Train experts in subjective probability estimation and elicit estimates. 4. Fill data entry templates.
Model testing and refinement 1. Test and review model output with experts. 2. Make model refinements and check errors 3. Define scenarios to be modeled.
Model output and interpretation 1. Run scenarios and sensitivity analysis 2. Review output with experts and stakeholders, including feedback from two virtual project workshops. 3. Identify key uncertainties, and develop insights into actions that could increase upsides and decrease risks. 4. Document the model, data sources, resources and insights.
Model handover 1. Identify and train experts in use of the model. 2. Identify a potential institutional home for hosting the model.

Simulations were run in Microsoft Excel using freely-available SIPmath™ tools,[1] which allow calculations to be done in the same way as single numbers, but behind the scenes the calculations are performed on probability distributions, stored as an array of possible outcomes. In the SIPmath Standard, uncertainties are communicated as data arrays called SIPs (stochastic information packets). For example, the SIP representing the roll of a die would be expressed as thousands of outcomes, which can be stored in Excel or a database.

The model input used metalog distributions (Keelin 2016), which are a flexible form of probability distribution that allow for easy input from disparate data sources and expert elicitation. Metalogs require users to only enter values for the 10th, 50th and 90th percentile of a variable, and optionally upper and lower bounds.

The model used an annual time step from present to 2040 and results were summarized in tabular and graphical form. Simulations for scenarios of interest to experts and policy makers were generated

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[1] Sipmath™ Modeller Tools. https://www.probabilitymanagement.org/tools

and displayed using a dashboard. The project team members were also able to interactively change input values and instantly view the outcomes.

The ranges in the simulated results are subject to the input data ranges used and the assumptions included in the model. The model is intended as a learning tool with which to explore likely outcomes of different assumptions.

Decision to be modeled

Initially the model was designed to project the adoption and differential impacts of SPaRC (KUSUM-C) compared with other forms of non-solar irrigation in all of India. In other words, the decision being modeled can be framed as “Is SPaRC a good bet compared with non-solar irrigation considering risks and net returns?” However, iterative consultation with experts led to several revisions of the model scope as follows:

- Extension of the model to compare KUSUM-C with KUSUM-A, as a competing model. KUSUM-A is based on substation-level solar power plants that provide farmers with direct solar power for irrigation.
- Consideration in the model of areas that are groundwater limited compared with areas where groundwater is non-limiting.
- Restriction of the model to Gujarat State initially due to the diverse range of conditions in different parts of India, and the more plentiful data and experience in Gujarat. However, the model structure was made generic and can be parameterized with data for other states as required.

Model structure and assumptions

The model structure was refined through iterative consultation with experts (Figure 1). The nested levels of aggregation of net benefits included in the model are: (i) farmers; (ii) aggregation of adopting farmers; (iii) distribution companies (DISCOMs) and local government; (iv) environmental; and (v) project level.

Incremental costs and benefits at farm level are aggregated according to the number of farmers adopting solar. The aggregated farm net benefits, the DISCOM and local government net benefits and net environmental impact are aggregated to give the overall project net benefit. Environment includes costs of water and greenhouse gas (GHG) emissions.

The various costs, benefits and risks considered in the model are shown in Table 2 and the more detailed list of input variables is given in the next section in Table 3. These were derived from literature review and approximately 67 person-hours of iterative consultation with experts.

Figure 1. Overall structure of the simulation model.

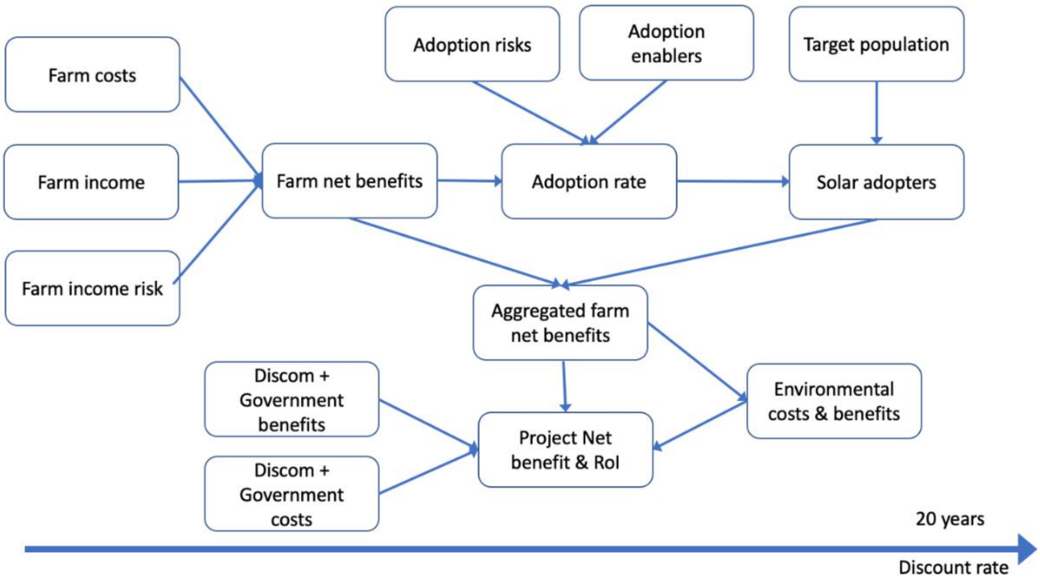


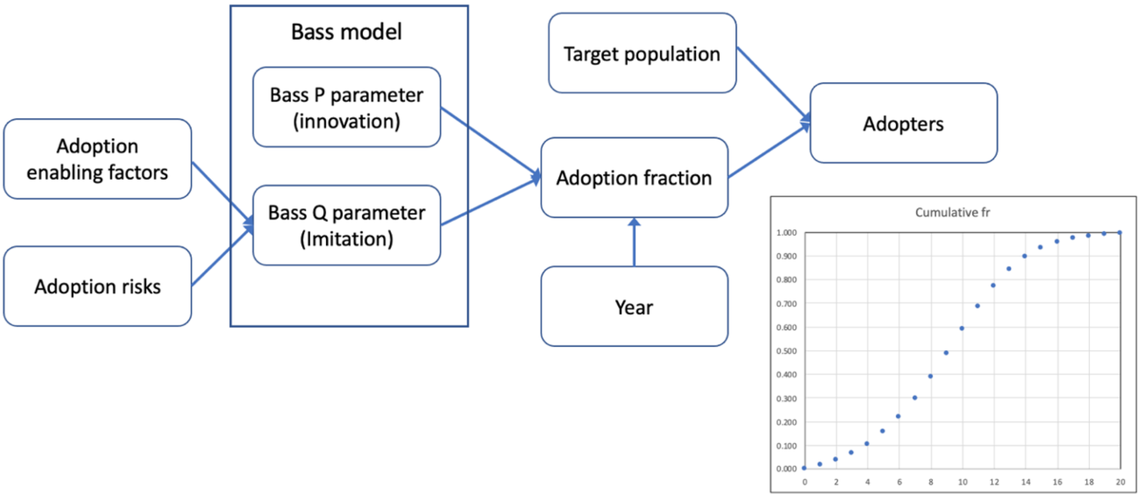
Table 2. Costs, benefits and risks associated with KUSUM-C and KUSUM-A.

KUSUM-C	**KUSUM-A**
Farmer costs	
• Initial investment of solar panel and pump • Loan repayment • Additional reoccurring costs	• None
Farmer benefits	
• Power savings due to more efficient irrigation • Savings due to adoption of solar (vs diesel or electricity costs) • Additional power generation • Sale of surplus power/water to neighbors • Sale of surplus power to the grid	• Increase in income due to more reliable/convenient power • Additional power available • Sale of surplus power to neighbors
Farmer risks	
• Lack of community structure and support services impedes adoption • Technical problems or theft decrease adoption • Low solar power tariff or low income reduces adoption • Overpumping increases water-pumping costs	• Lack of incentive to maintain feeders reduces benefit of reliable power • Power rationing by DISCOMs reduces income • Overpumping increases water costs • Farmers' negative perception of DISCOMs reduces adoption
Adoption enablers	
• High solar power tariff accelerates adoption • Promotion multiplier (communication, demonstration, policy) • Financing multiplier (private sector aggregators/government incentives)	• Promotion multiplier (communication, demonstration, policy) • Financing multiplier (private sector aggregators/government incentives)

DISCOM + local government costs	
• Capital costs (subsidies) • Execution costs	• Increase in supply cost due to extra consumption by farmers • Execution costs
DISCOM + local government benefits	
• Cost saving from solar power purchased • Savings from farmers taken off the grid • Reduction in losses	• Reduced cost of supplying electricity due to solar adoption
DISCOM + local government risks	
• None	• Lack of land availability for solar plants reduces adoption
Environment	
• Additional water use • Reduced GHG emissions from solar vs fossil fuel power generation	• Additional water use • Reduced GHG emissions from solar vs fossil fuel power generation

The target population of farmers is the number of farmers in the region of interest that have the potential to adopt solar irrigation. Adoption (Figure 2) is modeled using a Bass model,[2] which has been widely used to model technology adoption in industry, including photovoltaic systems. The Bass model has two parameters: the 'p' parameter determines the initial rate of adoption by 'innovators' and the 'q' parameter determines the subsequent adoption by 'imitators'. The Bass model determines the fraction of the target population that adopts each year. Its parameters are modified by various risk and enabling factors.

Figure 2. Overview of the model adoption component. The Bass model determines the cumulative fraction of the target population that adopts each year.



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[2] https://en.wikipedia.org/wiki/Bass_diffusion_model

KUSUM-C

In KUSUM-C, the main farm incremental cost is the capital cost of the solar panel and pump, modified by the fractions of the cost (i) subsidized by the government and (ii) covered by a commercial loan. The repayment period of the loan is specified. Additional reoccurring costs arise due to maintenance of the solar panel and pump, especially after the end of the loan period, when insurance expires.

Benefits derive from power savings from more efficient irrigation and surplus power generated over and above irrigation requirements, which can be either sold back to the grid or sold to neighbors. More efficient energy use is assumed due to the added incentive of a feed-in tariff and there are also chances that irrigation pumping demand might reduce. There is no evidence yet that farmers will invest in efficient irrigation – efficient irrigation technologies have been promoted through high government subsidies throughout India, but have received a rather lukewarm response. One major reason for this may be that farmers have never had any incentive to become efficient irrigators. SPaRC may provide that incentive.

Sales of power or water to neighbors are considered synonymous and the distribution of water yield per unit of solar energy is used as a conversion factor between the two. The partitioning of power between sale of power to the grid or to neighbors is conditioned on the relative prices of the feed-in tariff and the price of selling power to neighbors. Savings due to adoption of solar for pumping are due to the fact that farmers will not have to pay electricity or diesel fuel bills. For example, farmers in Gujarat may consume around 800 kWh per horsepower (hp) per year and with an average load of 11 hp, farmers pay around USD 80 every year in electricity bills.

Farmers face various risks that may affect either adoption or income directly. KUSUM-C requires a well-established community structure to operate and where this is not in place then adoption may be reduced, and additional resources will be required to create such structures. Cooperatives are needed because (i) individual solar systems are very small and farmers are not expert enough to take care of maintenance issues; and (ii) when farmers form collectives, they can better explore buyers for their energy. Technical problems or theft can influence farmers' perception of solar irrigation and reduce adoption.

Adoption rates are dependent on the feed-in tariff. Increases in tariff increase adoption rate, while reduced tariff reduces adoption rate relative to the baseline. Increases in water pumping risk further drawing down water tables in groundwater-limited areas and the model simulates an increase in the cost of pumping each unit of water as a function of additional pumping. Various other factors may enable more rapid adoption, such as promotional campaigns and financial incentives.

DISCOMs or local governments incur the cost of subsidizing the capital costs of solar pump systems and the execution costs associated with maintaining feeders. DISCOMs make savings from taking farmers off the grid through the reduced supply of subsidized power to farmers. They obtain Renewable Energy Credits for each kWh of solar energy generated by farmers. The energy that was earlier supplied to farmers at a loss can now service industrial and domestic consumers – both of which add to DISCOMs' profits. DISCOMS also make savings as a result of a reduction in technical, distribution and commercial losses associated with providing power. For example, in Gujarat, reductions in transmission and distribution losses are as high as 40%. This benefit alone can finance KUSUM-C.

The model allows water use to increase or decrease, depending on the price incentive to sell power/water to neighbors and the additional cost of water pumping due to water table drawdown. An 'environmental' water price is used to compute the environmental cost of water used. Reduction in GHG emissions through adoption of solar uses whole-lifecycle benefits versus the use of fossil fuel energy. A carbon price for CO_2 equivalents is used to monetize this benefit.

KUSUM-A

In KUSUM-A, farmers do not incur costs. The benefits accrue from an increase in income due to more reliable power, having additional power available and the sale of power/water to neighbors. More reliable power can increase income by avoiding damaging periods with no access to electricity during power cuts or rationing.

Under KUSUM-A, farmers might use additional power because they will not be limited to the amount of energy generated from a small number of panels on their farm, as would be the case in KUSUM-C. Instead of getting 8 hours of power during the day for 15 days, and 8 hours at night for the next fortnight, under KUSUM-A, they will have 8 hours of daytime power every day. There will not be lower discharges of power in morning and evening because the solar plant will be much larger than their own pump size, and so they will have access to unlimited power. Hence, shifting from 8 hours per day/night supply to 8 hours per day supply may result in an increase in farmers' power consumption. In addition, solar plants will be located at substation level with a capacity of 2 to 10 MW at peak load.

Farmers' income risks include power disruptions due to DISCOMs not maintaining feeders; power rationing by DISCOMs; and overpumping. A lack of incentive for DISCOMs to maintain feeders can occur if DISCOMs are compensated by state governments for energy used by farmers. DISCOMs are also under constant pressure from local and state-level politicians not to penalize farmers for any wrongdoing. DISCOMs can therefore see farmers as a nuisance, rather than as paying and valued customers. Power rationing by DISCOMs interrupts irrigation schedules and can reduce income. Overpumping will increase water pumping costs in groundwater-limited areas, as explained above. Farmers may generally have negative perceptions of DISCOMs due to factors such as rationing during the peak irrigation season and slowness in repairing transformers during the peak season. However, with time under KUSUM-A, a positive perception may develop. Adoption enablers are the same as for KUSUM-C.

DISCOMs incur costs due to extra power consumption by farmers having unlimited access to daytime power, resulting in increased consumption. Field studies have shown that off-grid solar pump owners pump more groundwater than their diesel and electric counterparts. DISCOMs have a benefit of reduced cost of supplying electricity in KUSUM-A due to (i) the feed-in-tariff for new solar plants being lower than the average power purchase cost for most electricity utilities; and (ii) savings on HT transmission losses due to distributed generation.

A risk for DISCOMs with KUSUM-A is the unavailability of land for substations. The opportunity cost of land will be very high as most of the substations are located in suburban areas. Renting or purchasing land near to substations on the scale of 5 acres of land for each megawatt of peak power is also difficult. Renting government land is even more difficult as it would require clearance from several departments. This constraint could increase the cost of energy generation.

Environmental costs and benefits for KUSUM-A are represented in the same way as for KUSUM-C.

Data input

All input variables and parameters are represented as probability distributions formulated from metalog distributions, where:

p0 = the minimum possible value.
p10 = the lowest likely value. The value is unlikely to be lower than this value 10% of the time or in 10% of cases.
p50 = the median value. The value that is most likely.
p90 = the highest likely value. The value is unlikely to be higher than this value 10% of the time or in 10% of cases.
p100 = the maximum possible value.

The input variables are listed in Table 2 and the input values used are documented in the model which, together with the supporting literature and presentations, is available at: https://www.dropbox.com/sh/9a6r5u5tjm0s3hr/AAB0Kfw9ojKdZXaCwNJ40KqAa?dl=0.
The total consultation time with experts was about 20 hours over six months, plus a workshop with experts from the IWMI-Tata Water Policy Research Program (ITP) and a virtual validation workshop with a wider set of stakeholders (see main report). Key experts were trained in probability estimation and reviewed the data input sheets and results.

Table 3. List of model input variables.

Adoption	**Definition (all are entered as probability distributions)**
Target population (no. of farmers)	The number of farmers in the target area that have potential to adopt solar irrigation
Farm size (ha)	Farm size of irrigation farmers
Bass p value	Coefficient in the Bass adoption model that determines the initial rate of adoption by innovators. The Bass model determines the fraction of the target population that adopts each year
Bass q value	Coefficient in the Bass adoption model that determines the rate of adoption by imitators
KUSUM C	
Farmer incremental costs KUSUM-C	
Pump load size (kW)	Pump capacity expressed as load
Oversizing ratio	Rated capacity of the solar panel array (kW peak) divided by the rated pump capacity (kW)
Pump + solar panel price per unit oversized adjusted load (USD/kW)	Price (USD) of solar panel + pump expressed per unit of oversized adjusted load (kW)
Subsidy fraction of initial investment	Fraction of the initial investment in solar panel/pump that is subsidized
Commercial loan fraction of initial investment	Fraction of the initial investment in solar panel/pump that is provided via a commercial loan
Loan repayment period (years)	Repayment period for the commercial loan
Additional reoccurring costs (USD)	Additional reoccurring costs associated with maintenance of solar panel and pump
Farmer incremental income KUSUM-C	
Power equivalent used for normal irrigation (kWh/yr)	Amount of power used for normal irrigation practices on a farm
Excess solar power generated (kWh/yr)	Solar power generated in excess of normal irrigation needs

Fraction of power saved due to more efficient irrigation	Fraction of power normally used for irrigation that is saved due to more efficient irrigation with solar pumping
Water yield per unit energy (m^3/kWh)	Conversion factor used to convert water pumped per unit energy
Water price (USD/m^3)	Environmental price of water, used to place an environmental value on water use
Electricity sale price back to grid (USD/kWh)	Tariff price for sale of power back to the grid
Irrigation sale price neighbors (USD/kWh)	Price gained for sale of water to neighbors, expressed per unit of equivalent energy required for pumping
Savings due to adoption of solar for pumping (USD/yr)	Savings from using solar instead of diesel or electric pumps
Increase in income due to more reliable/convenient power (USD/yr)	Increase in income due to more reliable power from having own solar source (e.g., from more timely irrigation compared with periods of power outages)
Farmer income risks KUSUM-C	
Overpumping risk coefficient	Coefficient that determines the shape of the relationship between the cost of pumping and the amount of additional water pumped, reflecting increased pumping costs as a result of water table drawdown in dry areas
Adoption risks KUSUM-C (0–1 scale; 0 = no risk)	
Lack of community structure	Adoption risk factor due to risk of lack of existing community structures, which makes it more difficult for adoption to occur
Technical problems or theft become common	Risk factor for technical problems or theft as a disincentive for other farmers to adopt
Research/policy intervention impacts on adoption KUSUM-C	
Promotion multiplier (communication, demonstration, policy)	Adoption multiplier (>1) that fractionally increments adoption rate due to efforts that promote adoption, such as communication, demonstration or policy interventions
Financing multiplier (private sector aggregators/ government incentives)	Adoption multiplier that fractionally increments adoption rate due to provision of financial incentives
DISCOM + government costs KUSUM-C	
Solar pump subsidy fraction contributed by central government	Fraction of the solar panel/pump cost that is borne by government
Execution cost (% of capex)	Cost of maintaining solar power systems (e.g., feeders) that allow buy-back of power to the grid, expressed as a percentage of capital expenditure on their establishment
DISCOM + government benefits KUSUM-C	
Savings from farmers taken off the grid due to direct subsidy (USD/farmer/yr)	Amount of savings that DISCOMs realize due to reduced supply of subsidized power
Reduction in losses due to implementation of KUSUM-C (USD/farmer/yr)	Amount of savings that DISCOMs realize due to reduction in technical, distribution and commercial losses

DISCOM + government risks KUSUM-C	
None	No costs were factored
KUSUM-A	
Farmer costs KUSUM-A	
None	No costs were factored
Farmer income KUSUM-A	
Power equivalent used for normal irrigation (kWh/yr)	Amount of power used for normal irrigation practices on a farm
Increase in income due to more reliable/convenient power (USD/yr)	Increase in income due to having more reliable power from own solar source (e.g., from more timely irrigation compared with periods of power outages)
Extra grid power used (kWh/yr)	Additional (excess) grid power used, over and above power used for normal irrigation
Fraction of excess power used for pumping	Fraction of the excess power generated that is used for pumping water
Water yield per unit energy (m^3/kWh)	Conversion factor used to convert water pumped per unit energy
Water price for additional water used (USD/m^3)	Environmental price of water, used to place an environmental value on water use
Farmer income risks KUSUM-A (0–1 scale; 0 = no risk)	
Lack of incentive to maintain feeders reduces benefit of reliable power	Risk factor that reduces income due to DISCOMs not maintaining feeders, resulting in unreliable power
Power rationing by DISCOMs	Risk factor that reduces income due to rationing of power by DISCOMs
Overpumping risk coefficient	Coefficient that determines the shape of the relationship between cost of pumping and the amount of additional water pumped, reflecting increased pumping costs as a result of water table drawdown in dry areas
Adoption risks KUSUM-A (0–1 scale; 0 = no risk)	
Farmers' negative perception of DISCOMs reduces adoption	Risk factor that reduces adoption in response to farmers' negative perception of DISCOMs, e.g., due to non- or late payments
Research/policy intervention impacts on adoption KUSUM-A	
Promotion multiplier (communication, demonstration, policy)	Adoption multiplier (>1) that fractionally increments adoption rate due to efforts that promote adoption, such as communication, demonstration or policy interventions
Financing multiplier (private sector aggregators/ government incentives)	Adoption multiplier that fractionally increments adoption rate due to provision of financial incentives
DISCOM + government costs KUSUM-A	
Increase in supply cost due to extra consumption by farmers (USD/farmer/yr)	Additional cost to DISCOMs resulting from extra consumption of power by farmers when using solar irrigation

Execution cost (USD/farmer/yr)	Costs of execution and land lease
DISCOM + government net benefits KUSUM-A	
Reduced cost of supplying electricity due to solar (USD/farmer/yr)	Savings due to reduced cost of supplying electricity from solar sources
DISCOM + government risks KUSUM-A (0–1 scale; 0 = no risk)	
Land unavailable for solar plants reduces adoption	Risk factor reducing adoption due to scarcity of land available for setting up solar banks
KUSUM-C and KUSUM-A	
Environmental benefit	
Reduction in GHG emissions from solar adoption (t CO_2eq/kWh)	Whole-lifecycle reduction in GHG emissions as a result of using solar versus fossil fuel energy sources
Carbon price (USD/t CO_2eq)	Carbon price per unit of CO_2 equivalent
Financial	
Discount rate (fraction)	Discount rate

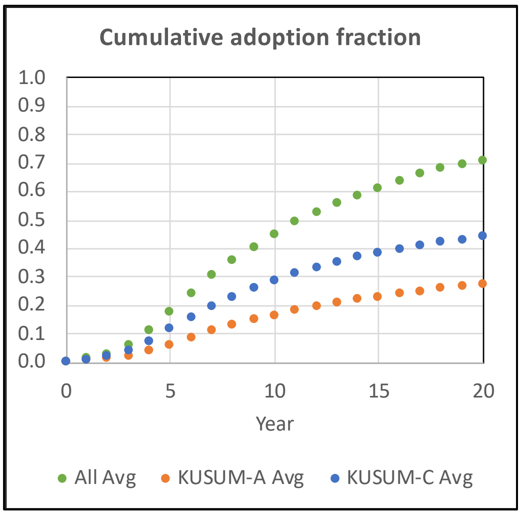
Model output

All model outputs are calculated as probability distributions and stored as SIPs with 1000 Monte Carlo trials. Results are summarized as expected values (EV), the 10th and 90th percentiles, or cumulative probability curves. A dashboard is available that allows users to enter p10, p50 and p90 values of selected variables and interactively view changes in key metrics graphically. This provides for simulating selected scenarios that experts had identified as being of particular interest during the feedback workshops.

Adoption

The simulations using the input distributions for the baseline situation projected that, on average, about 72% of the target population would have adopted solar irrigation by 2040 (Figure 3). KUSUM-C accounted for about 61% of adopters, while KUSUM-A accounted for 39% of adopters. This higher adoption of KUSUM-C is largely driven by its increased profitability compared with KUSUM-A. However, there was large uncertainty around these expected values due to the wide range of Bass p and q parameters used. There is currently little data with which to calibrate the Bass parameters and therefore monitoring of adoption rates will have high value for improving the prediction of outcomes.

Figure 3. Expected values of the time course of the cumulative adoption fraction of the target population for KUSUM-C, KUSUM-A and their total.



Net Present Value

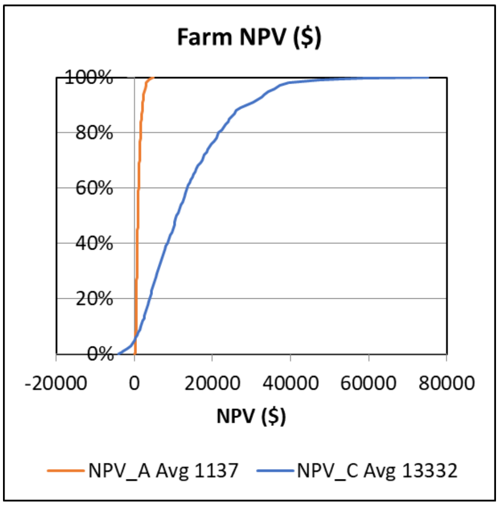
Net present values (NPVs) at different levels of aggregation at year 2040 are shown in Table 4. Expected values of farm-level NPV are over 10 times greater for KUSUM-C than KUSUM-A. The high net income in KUSUM-C is driven by sale of power back to the grid (about two-thirds of the income on average) and savings due to adoption of solar (about one-third of the income on average). The higher aggregated NPV for KUSUM-C reflects the higher farm income and the higher adoption rate.

Table 4. Distribution of net present values (NPV) in USD in 2040 at different levels of aggregation. The expected value (EV) and the 10th and 90th percentile values are shown. Units of millions are denoted with 'm'. Greenhouse gas (GHG) benefits are included.

	Net present value (USD)		
Level	**NPV 10th percentile**	**NPV EV**	**NPV 90th percentile**
Farm KUSUM-C	1,720	13,332	28,938
Farm KUSUM-A	431	1,137	2,128
Aggregated KUSUM-C	-1 m	3,358 m	10,184 m
Aggregated KUSUM-A	1 m	183 m	463 m
Aggregated all	1 m	3,541 m	10,454 m
DISCOM KUSUM-C	-138 m	1,014 m	3,086 m
DISCOM KUSUM-A	-353 m	-65 m	146 m
DISCOM all	-263 m	949 m	3,047 m
Water KUSUM-C	0 m	92 m	248 m
Water KUSUM-A	-327 m	-125 m	0 m
GHG KUSUM-C	1,046 m	1,032,194 m	2,352,328 m
GHG KUSUM-A	549 m	307,003 m	806,512 m
Environ all	2,202 m	1,339,163 m	3,235,047 m
Project	2,318 m	1,343,654 m	3,251,793 m

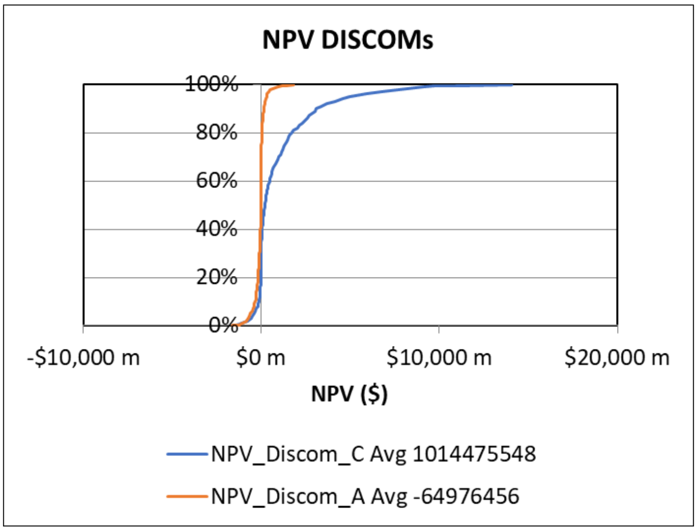
The farm-level distribution of NPV is much wider in KUSUM-C than KUSUM-A and there is a 5% chance of making a loss in KUSUM-C (Figure 4) due to combinations of lower income and higher discount rates in some trials. However, there is a large upside tail on KUSUM-C, with a 10% chance of obtaining over USD 30,000/ha discounted net benefit over 20 years. Further disaggregation of the downsides and upsides is warranted and would provide pointers to which policies may increase opportunities and reduce risks.

Figure 4. Cumulative probability distributions of farm level NPV for KUSUM-C and KUSUM-A.



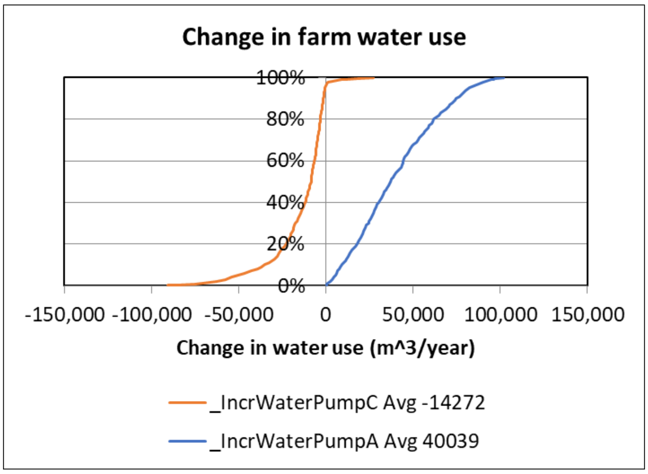
NPV for DISCOMs plus local government (abbreviated to DISCOMs) has a positive expected value for KUSUM-C but negative for KUSUM-A (Table 4). There is a 27% chance of loss for DISCOMs with KUSUM-C compared with 67% in KUSUM-A and a large upside opportunity in KUSUM-C, largely determined by variation in the size of the savings from taking farmers off the grid (Figure 5).

Figure 5. Cumulative probability distributions of NPV for DISCOMs plus local government in KUSUM-C and KUSUM-A.



KUSUM-C saves water on average (Table 4) and there is no chance of an increase in water use using the default data inputs (Figure 6), whereas KUSUM-A has a 90% chance of increasing water use. The former is due to more efficient irrigation in KUSUM-C and the incentive to sell power to the grid as opposed to increased pumping for sale of water to neighbors.

Figure 6. Cumulative probability distributions of change in farm water use in KUSUM-C and KUSUM-A.



Reductions in GHG emissions are massive (Table 4), at over one trillion USD (long form) on average in KUSUM-C and one-third of this amount in KUSUM-A. Emissions are calculated using whole-lifecycle emission reductions with solar compared with fossil fuel power, and using a distribution of carbon prices based on the State and Trends of Carbon Pricing published by the World Bank (2019). Accounting for GHG benefits, either solar irrigation scheme gives little chance (0.5%) of loss at the project level and gives a return on investment (ROI) of over 122,000%. Given the current lack of GHG payment mechanisms, an option is included to omit GHG benefits, which then gives a project-level average ROI of 349% with a 15% chance of loss. Further investigation is warranted into what combination of factors lead to project-level losses.

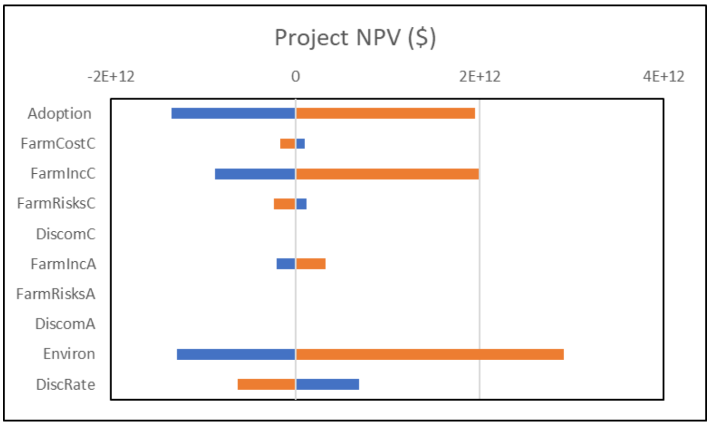
Sensitivity analysis

Stochastic sensitivity analysis was conducted by sequentially changing groups of variables to their 10th and 90th percentile values, with all other variables left as stochastic. The results are displayed as a Tornado diagram, which shows the change in project-level NPV relative to its expected value as a result of changing the target group of variables to their 10th or 90th percentile values.

When GHG benefits are included (Figure 7), variation in project NPV is dominated by the variation in environmental benefits. Results are also sensitive to adoption parameters and the farm-level benefits of KUSUM-C, especially on their upside. NPV was also sensitive to discount rate, which ranged from 5% to 15%.

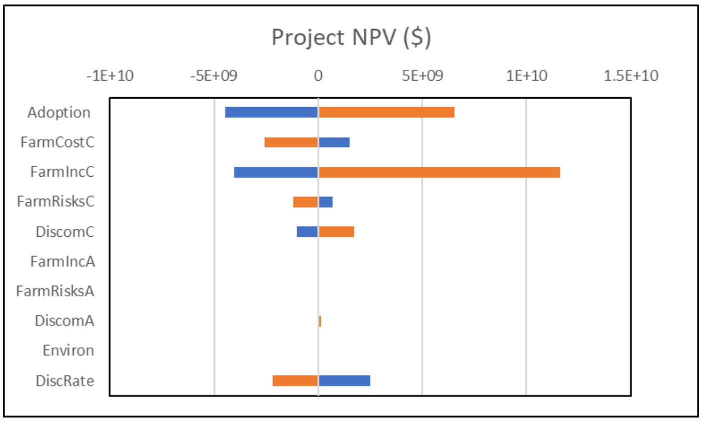
When GHG benefits are excluded (Figure 8), NPV is no longer sensitive to environmental benefits, and sensitivity is dominated by the upside of farm-level benefits for KUSUM-C, with the downside of KUSUM-C costs also playing in. Adoption factors remain as an important influence. More detailed decomposition of the farm-level benefits of KUSUM-C and better estimates of adoption parameters are warranted.

Figure 7. Stochastic sensitivity analysis of different variable groups displayed as a Tornado diagram when greenhouse gas benefits are included. The diagram shows the change in project NPV when a group of variables is set to its 10th percentile value (blue bars) or its 90th percentile value (orange bars).



Adoption = Adoption factors; FarmCostC = Farm costs for KUSUM-C; FarmIncC = Farm income benefits for KUSUM-C; FarmRisksC = Farm risk factors for KUSUM-C; DiscomC = DISCOM + local government costs, benefits and risks for KUSUM-C; FarmIncA = Farm income benefits for KUSUM-A; FarmRisksA = Farm risk factors for KUSUM-A; DiscomA = DISCOM + local government costs, benefits and risks for KUSUM-A; DiscRate = Discount rate. Note there are no Farm costs for KUSUM-A.

Figure 8. Stochastic sensitivity analysis of different variable groups displayed as a Tornado diagram when greenhouse gas benefits are excluded. The diagram shows the change in project NPV when a group of variables is set to its 10th percentile values (blue bars) or its 90th percentile values (orange bars).



Adoption = Adoption factors; FarmCostC = Farm costs for KUSUM-C; FarmIncC = Farm income benefits for KUSUM-C; FarmRisksC = Farm risk factors for KUSUM-C; DiscomC = DISCOM + local government costs, benefits and risks for KUSUM-C; FarmIncA = Farm income benefits for KUSUM-A; FarmRisksA = Farm risk factors for KUSUM-A; DiscomA = DISCOM + local government costs, benefits and risks for KUSUM-A; DiscRate = Discount rate. Note there are no Farm costs for KUSUM=A.

Additional indicators

NPVs were presented in Table 4. In this section the results for additional indicators at Year 20 are presented (Table 5). The wide (100-fold) range in the number of adopters reflects the wide range in the Bass model adoption parameters, which span the global range of adoption rates for photovoltaic technology. At the farm level, KUSUM-C incurs a small chance of loss, as previously described, whereas KUSUM-A has no chance of loss. Consequently, the number of farmers profiting is 97% of adopters on average. The wide range in irrigated area reflects the wide range of adoption rates and its distribution between KUSUM-C and KUSUM-A.

There are opportunities for moderate water savings (farm water use of -14,300 $m^{3/}$yr on average) with KUSUM-C, even at the 90th percentile, compared with increased water use in KUSUM-A (40,000 $m^{3/}$yr on average). The project-level ROI is very large on average, even without considering GHG benefits, but is slightly negative at the 10th percentile. Including GHG benefits, the ROI is extremely high at all levels of probability.

Table 5. Distribution of values of additional indicators in 2040. The expected value (EV) and the 10th and 90th percentile values are shown.

Indicator	10 percentile	EV	90 percentile
Target population (number of farmers)	804,469	997,505	1,193,770
Adopters KUSUM-C	7,704	439,940	828,491
Adopters KUSUM-A	4,861	268,260	567,569
Adopters total	13,594	708,201	1,139,426
Chance of farm-level loss KUSUM-C	-	5%	-
Chance of farm-level loss KUSUM-A	-	0%	-
Number of farmers profiting	-	687,963	-
Irrigated area KUSUM-C (ha)	7,732	476,093	1,116,923
Irrigated area KUSUM-A (ha)	5,100	292,575	705,821
Irrigated area total (ha)	13,671	768,668	1,737,344
Change in farm water use KUSUM-C (m^3/yr)	-35,087	-14,272	-1,342
Change in farm water use KUSUM-A (m^3/yr)	9,304	40,039	74,914
Return on investment without GHGs (%)	-29	349	882
Return on investment with GHGs (%)	4,088	112,059	273,393

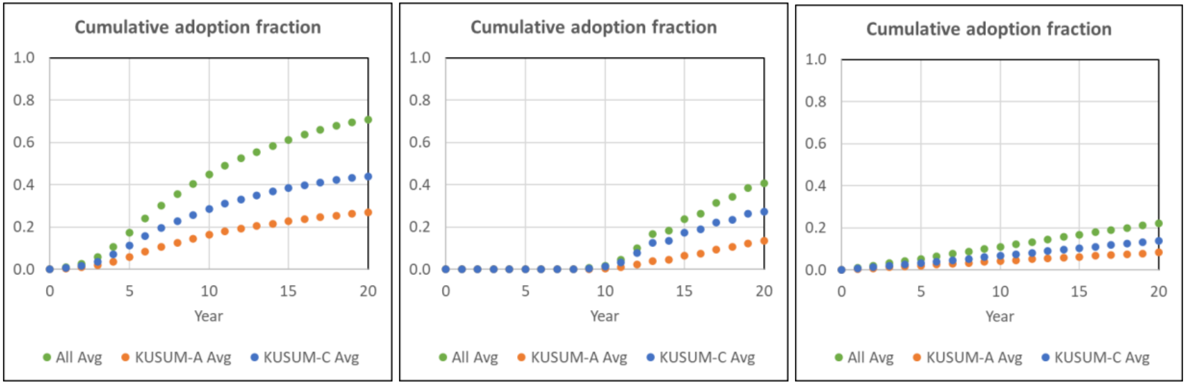
Model scenarios

Several scenarios are simulated, identified by experts and through stakeholder workshops as of importance for policy decision making and supporting research. The choice of scenarios was also informed by the results of the sensitivity analysis.

Adoption parameters

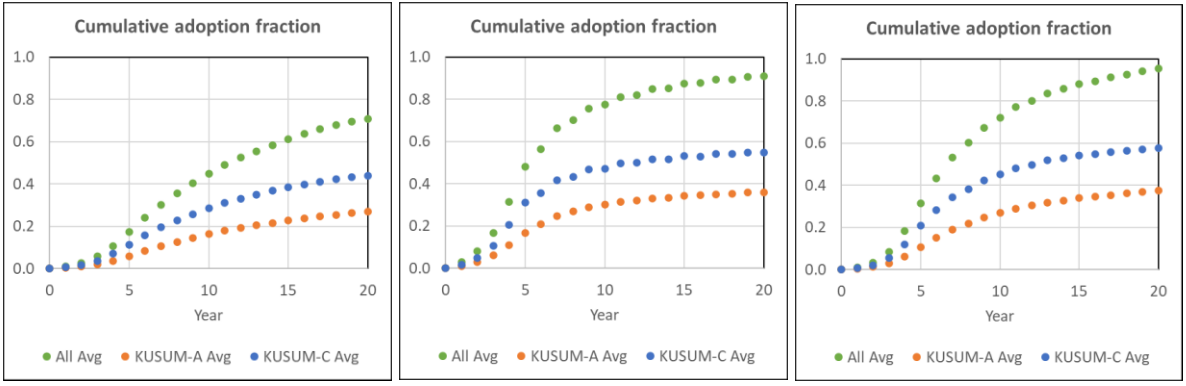
The Bass adoption model p and q parameters were allowed to vary widely, covering the range reported from a global review of photovoltaic adoption studies across 10 countries (Yang et al. 2018). Reducing the Bass model innovation parameter, p, to low (10th percentile value) delayed pick-up in adoption until after Year 10 (Figure 9b) compared with the base case when all parameters are left as stochastic (Figure 9a). When the mimicking parameter, q, is set to low, there is a slow, steady increase in adoption. When both p and q parameters are set to low, there is virtually no adoption over the 20 years (not shown).

Figure 9. Response of cumulative adoption fraction over time (a) for the base case, and (b) with the Bass model p parameter at its 10th percentile value and (c) with the Bass model q parameter at its 10th percentile.


(a) (b) (c)

When either the Bass p or q parameters are set to high (90th percentile values), then almost complete (100%) adoption occurs at 20 years (Figure 10b, 10c). When both p and q parameters are set to high, then complete adoption occurs by Year 5. Further research on adoption rates of solar technology in Asian countries is warranted to reduce the uncertainty on expected adoption rates.

Figure 10. Response of cumulative adoption fraction over time (a) for the base case, and (b) with the Bass model p parameter at its 90th percentile value and (c) with the Bass model q parameter at its 90th percentile.

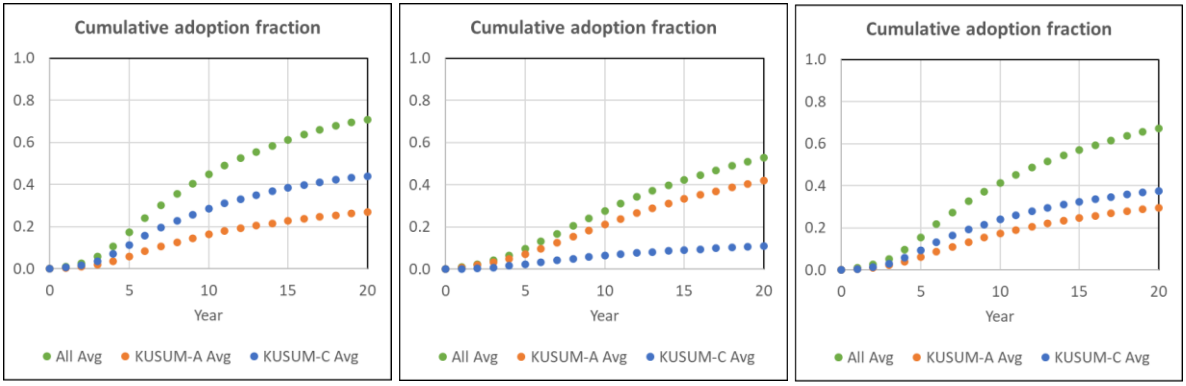

(a) (b) (c)

Subsidies and loans

Currently, the capital cost of solar pumping equipment (solar panel and pump) in KUSUM-C is subsidized for farmers by both central government (30%) and local government (30%). The remaining 40% of the capital cost is taken as a loan by farmers from local banks over a period of six years. The profitability and adoption of KUSUM-C may be strongly influenced by the amount of subsidy and the loan period.

When subsidy is completely removed (Figure 11b), overall adoption of solar irrigation is reduced by only about 10% by Year 20 compared with the base case (Figure 11a); adoption of KUSUM-C drops to a low level and adoption is dominated by KUSUM-A. This lower adoption of KUSUM-C is driven by the lower farm-level profitability, with expected NPV reducing from USD 13,500 to USD 8,000. The switch in adoption comes with a project-level environmental cost, increasing on average from USD 32 million in the base case to USD 149 million when subsidy is removed. This is due to reduction in water savings in KUSUM-C (-14,300 m^3/year) combined with increases in water use in KUSUM-A (40,000 m^3/year), and increased GHG emissions in KUSUM-A compared with KUSUM-C (Table 5). These translate into an increase in risk of loss at the project level, from 15% in the base case to 30% without subsidy. However, if farmers are able to take a 100% loan over 10 years, the average adoption dynamics are almost restored to those of the base case (Figure 11c).

Figure 11. Response of cumulative adoption fraction over time (a) for the base case, and (b) with removal of subsidy and (c) removal of subsidy and increase in loan to 100% of capital cost over a period of 10 years.



(a) (b) (c)

Tariff prices

Varying tariff prices for the sale of power back to the grid is considered a key policy lever. The value of the sale of water to neighbors is also important as it can provide an incentive to use power to pump more water to sell as opposed to selling the power back to the grid. The balance in prices is likely to determine farmers' behavior. There is also large variation in the pricing of water for sale to neighbors: in some areas where high-value crops are grown, water prices may be high, but in other areas there is no demand for water purchasing.

Adoption is not very sensitive to variation in tariff, although at a very low tariff the adoption rate of KUSUM-C converges to that of KUSUM-A (Figure 12b). However, farm water use in KUSUM-C switches from an average water saving of about 14,300 m^3/year in the base case to an increase in water use of about 19,600 m^3/year with very low tariff (Figure 13a, 13b). A high tariff slightly increases the adoption rate of KUSUM-C relative to the base case.

When the price for selling power to neighbors is set to zero, water savings in KUSUM-C increase to 33,700 m^3/year, more than double the water saving of the base case. An extreme scenario of no selling of power to neighbors produces an environmental benefit of USD 64 million compared with an environmental cost of USD 32 million in the base case.

Figure 12. Response of cumulative adoption fraction over time (a) for the base case, and (b) with a very low tariff (INR 1.2/kWh) and (c) a high tariff (INR 4.6/kWh).

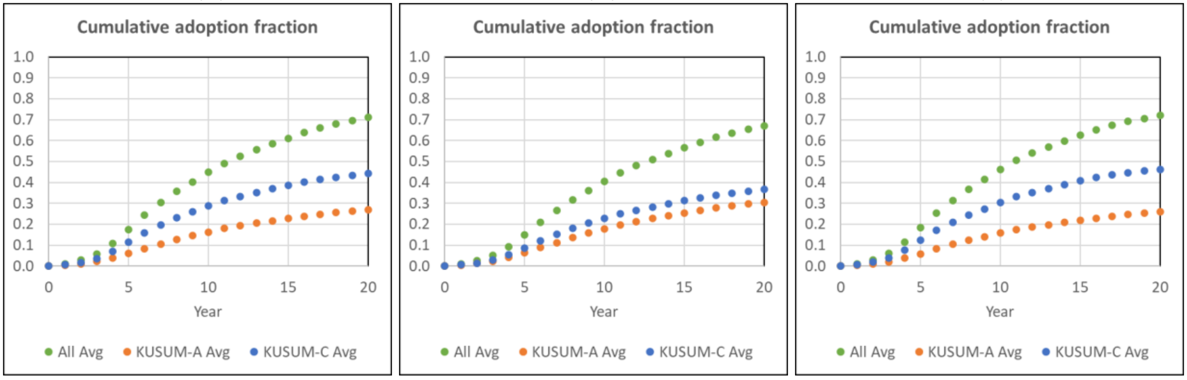
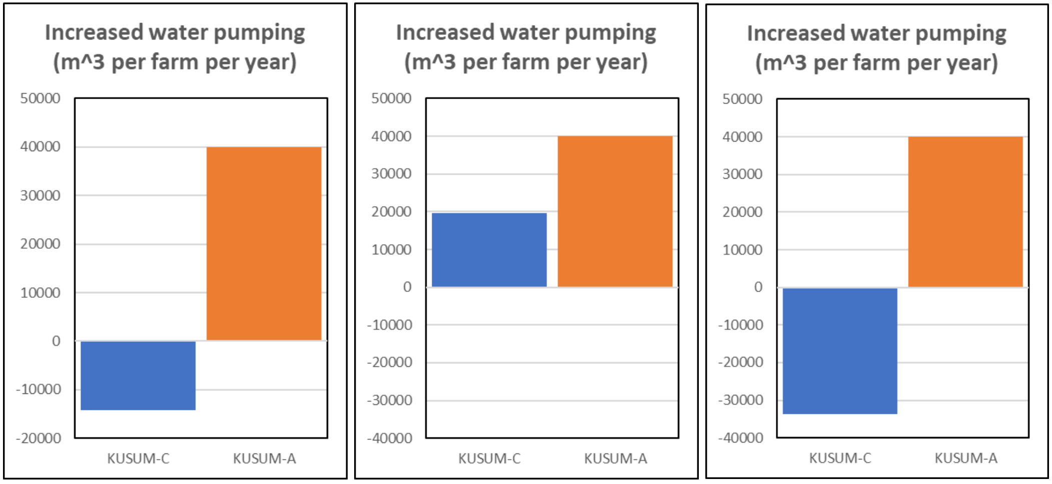

(a) (b) (c)

Figure 13. Response of farm-level water use (a) for the base case, and (b) with a low tariff (INR 1.2/kWh) and (c) with the base case tariff (INR 3.8/kWh) and zero price for selling power (water) to neighbors.


(a) (b) (c)

Capacity to support KUSUM-C

KUSUM-C requires a high level of community organization and competent local facilitating agencies to support its communication and roll-out. In Gujarat, there is already a high level of community organization from milk cooperatives and KUSUM-C has had a high level of promotion. However, in other states these structures may be less advanced and present an obstacle to the adoption of KUSUM-C. We would expect the adoption q factor to be reduced where there is less structure, which would result in a tendency towards the adoption pattern shown in Figure 9b, with a slow initial phase before adoption picks up. The length of the lag phase would be proportional to the time it takes to establish local community structures and local supporting organizations and develop capacity and community awareness.

Risk of non-payment by DISCOMs

The risk of non-payment by DISCOMs in KUSUM-C was raised by stakeholders as a significant risk. This would reduce the confidence of both farmers and banks and result in reduced bank lending. Reduced lending would favor adoption of KUSUM-A over KUSUM-C. If loans were unavailable, the simulations show an average adoption fraction at Year 20 of 0.4 in KUSUM-A versus 0.19 in KUSUM-C. This would increase water use and the chance of a project-level loss as shown in the scenario of reduced tariff.

Availability of land for KUSUM-A

A risk to the adoption of KUSUM-A is the difficulty DISCOMs may encounter in acquiring land for the solar banks. In cases where this risk is enhanced, the outcome is a lowering of the Bass model initiation parameter, q, which results in a tendency towards the adoption pattern in Figure 9b.

Low existing groundwater levels

In areas where existing groundwater levels are low, there may be large policy and farmer resistance to the adoption of solar irrigation due to the perception of increased groundwater depletion. Our simulations show potential for KUSUM-C to reduce water use, especially where feed-in tariffs are higher than the price of selling power to neighbors; in contrast, KUSUM-A is likely to increase water use. Therefore, the adoption of solar irrigation will depend heavily on communicating the benefits of KUSUM-C and ensuring supporting policies are put in place to favor its adoption.

Proposal to provide daytime power

There have been local government proposals to provide daytime power to farmers. This may disfavor adoption of KUSUM-C by taking away the benefit of more reliable power offered by KUSUM-C. However, generating power on-farm is always going to be more reliable than depending on any grid supply, even with the promise of daytime power. Perhaps more prominently, a daytime power alternative may make the transaction cost of community building and communication with KUSUM-C more pronounced.

With a daytime power scheme, farmers will need more convincing of the benefit of KUSUM-C and this may be reflected in a slower adoption rate for KUSUM-C (e.g., Figure 9b). The success of KUSUM-C will depend largely on how beneficial farmers perceive it to be.

However, giving all farmers daytime grid power may be difficult, and costly. DISCOM operations are most efficient if their ‘load curve’ is flat (i.e., constant demand for electricity throughout the day and year). The best way to achieve a near-flat load curve is to schedule power supply to farmers when nobody else wants it. With providing daytime power to farmers, this will become very difficult to achieve, unless there is a very rapid increase in solar generation capacity. Such a policy decision would strongly favor KUSUM-A, which can be rolled out much faster than KUSUM-C.

Policy implications

The simulations point to several implications for policy. Solar irrigation in general (whether KUSUM-C or KUSUM-A) provides the following expected values and risks by 2040 compared with non-solar alternatives, although the sizes of the value and risks vary according to the model or mixture of models:

- Increased farm income (USD 1,000 to USD 13,000 per farm);
- Water savings or increased water use at farm level depending on the model (saving of 14,300 m^3/yr to increased use of 40,000 m^3/yr);
- GHG benefits (USD 310,000 million to USD 1,030,000 million at project level);
- Chance of loss of 0 to 5% at farm level and 27% to 67% for DISCOMs + local government.

Therefore, while farm income and GHG reduction benefits are universal, the profitability for DISCOMs (including local government) and impacts on water use are strongly dependent on the model that is implemented. The above projections are expected, or average, values and there is a wide range in possible values, which must be taken into account and are an area for further policy research.

The differences in expected value and risks of KUSUM-C compared with KUSUM-A at 2040 are summarized in Table 6. Substantive increases in farm income and water savings only occur with KUSUM-C. However, as seen in the scenario analysis, these benefits are conditional on maintaining subsidies, or compensating for them through more favorable loan support, and maintaining tariffs for the sale of power to the grid. KUSUM-C is also a more attractive proposition to DISCOMs providing that mechanisms are found for providing the necessary level of institutional support. GHG benefits are three times higher in KUSUM-C compared with KUSUM-A.

There is some debate on the future trends in tariff prices and whether providers will incur a cost of subsidizing these if prices fall when they have provided a 25-year guaranteed tariff under a power purchase agreement. The scenario analysis shows that a low buy-back tariff will not incentivize farmers to reduce groundwater pumping and KUSUM-A and KUSUM-C will be more similar in terms of the lack of incentives for saving groundwater. On the other hand, if the government decides that, in the interest of reducing groundwater pumping, farmers will continue to get a higher buy-back tariff, then the subsidy burden on DISCOMs/state government/ministry (whoever pays the buy back) will increase and could perhaps negate the main purported benefit for DISCOMs. However, on the other hand, the savings for DISCOMs are much higher than just the cost of buying power and may far outweigh the cost of tariff subsidy. In addition, if tariff prices did go down, then farmers could come together as an independent power producer and sell power to the commercial sector, becoming competitors to the DISCOMs. For example, dairy plants in Gujarat are already considering investing in solar power to meet their energy needs and could contract farmer cooperatives to supply their power.

Table 6. Summary of values and risks for KUSUM-C versus KUSUM-A. NPV values are for Year 2040. Values are rounded; units of millions are denoted with 'm'.

Value	KUSUM-C	KUSUM-A
Additional farm net income (NPV)	USD 13,500	USD 1,000
Chance of income loss at farm level (%)	5	0
Change in water use at farm level (m^3/farm/yr)	-14,300	40,000
DISCOM + local government net income (NPV USD)	USD 1,000 m	-USD 60 m
Chance of income loss for DISCOM + local government (%)	27	67
GHG discounted benefits (USD)	USD 1,032,000 m	USD 307,000 m

KUSUM C is likely to face the strongest competition from KUSUM A when:

- Subsidies are decreased or removed;
- Loans are decreased;
- Tariff prices are reduced;
- Demand and price are high for buying water (e.g., cash crops);
- Non-payment by DISCOMs becomes prevalent;
- Groundwater is not limiting;
- Local institutions are weak;
- Land for solar banks is available;
- Daytime power is made available.

Priorities for further research and monitoring

The simulation results point to several areas where further research would have high value for improving estimates of solar irrigation benefits and for supporting its adoption and favorable outcomes:

1. Further literature review to narrow the Bass model parameter estimates using data for similar technology and regional situations.
2. India-wide research on causal factors determining tariff prices and incentives for selling water to neighbors.
3. Institutional mechanisms for supporting the adoption of KUSUM-C. For example, on which types of local institutions could be supported by local governments to build farm communities, liaise with DISCOMs and communicate potential KUSUM-C benefits.
4. Policy advocacy and communication strategies for conveying the potential income-water-energy benefits of KUSUM-C and conditions for its success to farmers, local government, DISCOMs and central government.
5. Factors that could reduce risks and enhance benefits for DISCOMs.
6. How to realize and distribute the GHG emission reduction benefits of solar power through payment or incentive schemes. Better estimates of how much fossil fuel solar irrigation is displacing versus other solar alternatives.
7. Run the model for other Indian states or diverse situations by adjusting values in the model input sheet and checking assumptions hold up in other states. Areas where there is groundwater stress and a weak history of community structures, in contrast to Gujarat, would be high-priority candidates.
8. Update the model to include any additional assumptions or comparisons that are of interest to researchers or policy makers, such as inclusion of a KUSUM-B/C hybrid, i.e., standalone microgrids in which surplus power is put to productive and paid use.

There was an additional suggestion to include in the model the social gain created through buying-back power from farmers instead of developers. This could be done by thinking through what tangible benefits would be observed if there was social gain or not.

Priorities for monitoring include:

1. Adoption rates of different solar irrigation models and associated factors;
2. Trends in subsidies and loans;
3. Tariff prices and water sale prevalence and pricing;

4. Additional farm incomes actually achieved, and water use patterns with solar irrigation. For example, case-control studies could be envisaged;
5. Types of local institutions supporting KUSUM-C and criteria for success;
6. Introduction of policies that could change incentives for the adoption of KUSUM-C and/or KUSUM-A (e.g., provision of daytime power).

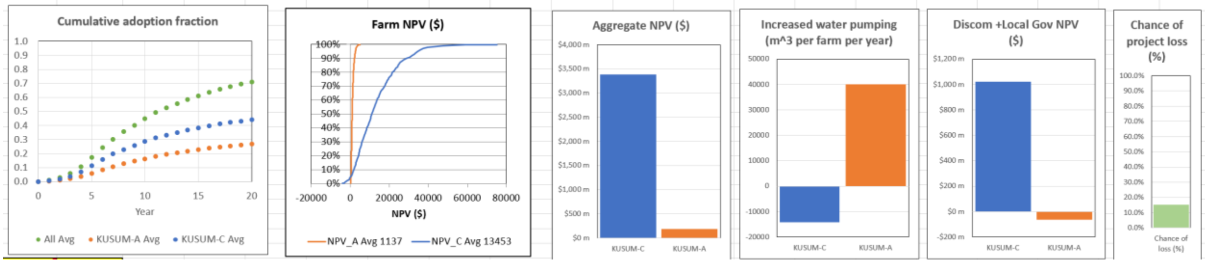
Adoption rate is the overriding uncertainty determining outcomes in the model and therefore has the highest value for further research and monitoring, both to narrow the uncertainty and to validate the causal factors affecting adoption. Of second priority are KUSUM-C benefits, especially factors that favor the upside opportunities for obtaining high farm income and large water savings, and actions that could further minimize the chance of loss. Of third priority is to better establish how to reduce risks for DISCOMs and exploit upside opportunities.

Model handover

The simulation model is intended to serve as a learning tool for researchers and policy makers. A simulation model dashboard is provided to make it easy for non-specialists to change values of key input variables (e.g., to low, 10th percentile; medium, 50th percentile; or high, 90th percentile levels, or more extreme levels) and immediately observe the response of outcome variables in graphical form (Figure 14). The model's data input sheet is on a separate, linked worksheet to facilitate use and contains fields for documenting data sources.

Ideally, ownership of the model would be taken over by an institution that could maintain, use and further develop it (see Recommendation 3 in the main report). Of particular interest is the potential to work with policy makers to show scenarios and results and help develop a better understanding of the benefits and trade-offs with alternative solar irrigation models. ITP has been proposed as one potential candidate for a hosting institution. Some financial and technical backstopping support may be required initially to make this happen and may be considered by WLE.

Figure 14. Model dashboard display, which allows users to visualize results interactively as values of key input variables are changed over their ranges.



A CGIAR enterprise platform for risk management

Data or information from applied research have no value unless they improve decision making. For example, decisions on what interventions should be promoted to provide the most favorable livelihood and environmental outcomes at least cost and risk. It is impossible to know what research will produce value without first quantifying the current state of uncertainty and then seeing which uncertainties are critical for outcomes. There is also strong demand from donors and other stakeholders for CGIAR to project and monitor benefits.

The CGIAR Monitoring, Evaluation and Learning Community of Practice (MEL) has shown interest in the decision analysis and modeling approach used in this study as an input to 'projected benefits' of CGIAR initiatives. The SIPmath^{TM} open-standard approach used in this study could provide the foundation for a CGIAR enterprise-wide platform for representing uncertainty and including uncertainty and risk in cost-benefit analysis. SIPmath^{TM} is readily accessible to everyone in Excel but is also applicable across platforms (e.g., R, Python). We therefore recommend this approach for consideration as a CGIAR-wide complement in ex-ante and ex-post impact evaluations, and for use in research project screening at various stage gates, based on projected benefits with increasing detail at each stage gate. WLE might share the results of this study with MEL and discuss its potential wider application (see Recommendation 4 in the main report).

Conclusion

The simulations have indicated that promotion of solar-powered irrigation using KUSUM-C is a good decision in Gujarat State. Compared with non-solar alternatives, KUSUM-C has potential to substantially increase farm profits with low risk, reduce water use and substantially reduce GHG emissions, while providing an opportunity for DISCOMs and local government to profit. There are significant upside opportunities for farmers to profit.

However, the benefits of KUSUM-C are strongly conditional on the maintenance of government subsidies, the availability of farmer loans and the presence of strong local community-based organizations and facilitators. Compared with KUSUM-C, promotion of KUSUM-A provides moderate GHG benefits but provides a lower level of net benefit to farmers, increases water use and poses a higher risk of DISCOMs and local government making a loss. KUSUM-A is more appropriate for areas with plentiful groundwater resources.

Adoption is projected to be higher with KUSUM-C than KUSUM-A under current conditions in Gujarat, but this situation would flip if subsidies were reduced or removed. The combined adoption of KUSAM-A and KUSAM-C is projected to benefit about 1 million farm families by 2040 and increase income for 97% of them. However, overall water use is expected to increase unless adoption is restricted to KUSUM-C only.

A number of priorities are identified for further research and monitoring, targeted at areas of greatest uncertainty and largest effect on outcomes. Recommendations are made for further application, maintenance and improvement of the model as a research and policy learning tool. These include (i) assisting ITP to take ownership of the model and (ii) the adoption of risk-return analysis, aided by SIPmath^{TM}, as a CGIAR enterprise-wide standard for impact projection.

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