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Quantifying environmental and economic benefits of grid-connected solar water pumps for irrigation in India

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Abstract: Grid-Connected Solar Water Pumps for irrigation are being favoured for developing countries, like India, primarily because of the available rural grid infrastructure. One of the major benefits of these systems is the provision of feeding excess energy into the grid. This increases the revenue of the farmer as well as avoid over-exploitation of groundwater resources. Over-exploitation of groundwater resources is a major threat both in stand-alone and grid-connected systems. This paper proposes a methodology to accurately estimate the excess energy available after meeting the energy required for feeding the water to a specific crop at a given location. With this the farmer will be able to estimate the additional revenue they will be getting through buy-back of excess energy and the utilities, the amount of excess energy available through these systems, for planning. This will help promote KUSUM, a scheme offered by the Government of India to solarize one million grid-connected pumps. The proposed methodology is implemented for a location in Andhra Pradesh based on the guidelines in the scheme and the results presented.

Keywords: Grid-connected Solar Water Pumps, KUSUM, Utilizability, Buy-back scheme, over-exploitation of ground water.

1. Introduction

Solar Water Pumps are being promoted for agriculture all over the world as they offer multiple benefits to farmers, utilities and the country at large. They provide clean, affordable and reliable energy, potentially reducing energy costs for irrigation. In rural areas, particularly in under-developed and developing countries, where diesel fuel is expensive or access to continuous power is lacking, they provide a relatively reliable, affordable and environment friendly energy alternative [1]. The farmers are assured of a reliable supply ensuring sustainable source of water supply providing them a sustained source of livelihood with these systems. With substantial drop in prices and improved capabilities of reaching deep wells up to 500 metres and discharge levels of 1,500 m^3/day, they are offering more opportunities for adapting these technologies for irrigation [2].

In India, at present, 30 million agriculture pumps are installed in the country out of which 10 million pumps use diesel as fuel. The consumption of electricity by the agricultural sector is about 17% of the total consumption. Both electricity and diesel are subsidised creating lot of burden on the Government. Many of the distribution companies in different states are able to provide supply to consumers only for 7 to 9 hours a day. With a need to address the shortage of power and climate change, the Government of India has started promoting off-grid solar pumps for irrigation with a subsidy. As on date, there are about 130,000 off-grid solar pumps installed in the country [3]. However, there are two disadvantages in these systems-economic and ecological. Their capital cost is 10-15 times that of diesel or electric pump making it difficult for the small and marginal farmers to adapt without major financial subsidy by the government.

Such capital intensive projects are viable only when their utilization is very high [4]. For example, India's diesel pumps operate on an average for only 460 hours / annum for irrigation [5] and a typical 5kWp solar pump runs for 500 hours / years (against its potential of 2500 hours per annum). A study in Rajasthan shows that there is evidence of over-extraction of ground water with access to solar powered irrigation with a capacity of 3 HP [6]. Therefore, the owner of a solar system is tempted increase his revenue by irrigating water intensive crops, increasing cropping intensity and selling the excess water. But this will cause over-exploitation of ground water causing ecological problem for aquifers. One of the solutions to conserve ground water is to buy-back the surplus energy to the grid. This would incentivise the water-and energy-use efficiency and augment the incomes of farmers [7]. Karnataka introduced Surya Raitha, a scheme offering a guaranteed buy-back of surplus power at a feed-in-tariff of Rs.5 per kWh providing additional annual income [8].

Another model for producing solar power as remunerative crop was introduced in Central Gujarat. It offers multiple benefits including controlling groundwater overexploitation, reducing the subsidy burden on Distributed Companies (DISCOMs), curtailing carbon footprint of agriculture, and help double farmer incomes [9]. Bradley Franklin has made an attempt to determine the optical cost of buy-back scheme by estimating the demand for irrigation water and electricity used for pumping for different seasons and locations in Punjab, India. He concludes that buy-back scheme could be based on seasonal and spatial demand variations for achieving significant savings in ground water pumping [10] with a few political implications.

Thus, solar water pumps for irrigation are not just a climate-friendly and reliable alternative source of energy for farmer. It should be thought of as a technology for more sustainable use of ground water resources, to create more inclusive financial and management structures and to foster more integrated thinking about solutions around the water-energy-food nexus [1]. For this to happen, feasibility studies on the potential use of solar pumps in specified districts or regions must first be carried out. They should take into account parameters like weather and soil data, slope of the terrain, crop requirements, water availability and government policies. Though there is published literature in different Indian states like, Punjab, Gujarat, Rajasthan and Karnataka, they do not consider any of the parameters. They are either successful case studies or the policies introduced by the governments with potential benefits and do not discuss the detailed methodology, data used etc. Since the authors have not come across such methodology in the literature, the present work makes an attempt to fill this gap.

The objective of this paper is to quantify the benefits to the farmer with the use of grid-connected solar water pumps under KUSUM (Kisan Urja Suraksha evem UthhanMahabhiyan), a scheme promoted by Government of India. Under this scheme, government plans to replace agriculture diesel pumps with solar pumps and solarize the grid connected electric pumps [11]. This paper presents a methodology to estimate monthly average hourly water requirement based on the crop, location and size of the land. Using the concept of utilization, excess energy available after meeting the load is calculated based on the size of the pump and solar system following the guidelines given in the scheme [12]. Thus, the average annual additional income to the farmer through buy-back scheme and more importantly, the amount of ground water saved can both be quantified i.e. spelt out in rupees and paise, thus providing a reliable metric to the farmer, the banker and the environmentalist. In addition, Solar Water Pump usage reduces the GHG (greenhouse gases) emission per unit of energy used for water pumping of 95 to 97 per cent as compared with pumps operated with grid electricity and 97to 98 per cent as compared with diesel pumps [13].

2. Proposed Methodology

This section presents the detailed methodology for quantifying the benefits of grid-connected solar water pumps under KUSUM. It consists of four steps as described below.

2.1 Estimation of water required

Crop irrigation requirements are computed using the guidelines provided by FAO [14] using Eq. (1) and Eq. (2). Crop coefficient, Kc for estimating Crop Evapotranspiration, ETois given in Table 1. Monthly average values of Evapotranspiration are calculated using Penman-Monteith method given in Eq. (1).

$$ET_o = \frac{0.408\,\Delta\,[R_n - G] + \frac{(\gamma \times 900)}{(T+273)} u_2 (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \text{ mm/day}, \quad (1)$$

Where,
R_n = Net radiation in MJ/m^2/day at the crop surface
G = Density of Soil heat flux in MJ/m^{2}day
u_2 = Speed of wind in m/s at 2 m height
T = Mean daily temperature of air in °C at 2 m height
e_s = Saturation vapour pressure in kP$_a$
e_a = Actual vapour pressure in kP$_a$
Δ = Slope vapour pressure in kP$_a$/°C
γ = Psychometric constant in kP$_a$/°C

Table 1. Crop coefficient of the Paddy for different growth stages.

Growth Stages	No.of days	Crop Coefficient (Kc)
Transplant of direct sowing	1-60 days	1.1
Mid-season	61-120 days	1.3
Before Harvest	121-150 days	1.0

The following Eq.(2) is used to estimate the monthly average daily peak water requirement, $W_{r.m}$ per acre (0.4 hectares).

$$W_{r,m} = \frac{C_a \times ET_O \times K_c \times P_c \times W_a}{E_u} \text{ m}^3\text{/day} \quad , \qquad (2)$$

2.2 Selection capacity of solar PV system (PM-KUSUM scheme offered by Govt. of India)

(i) Capacity of the solar PV system is same as the capacity of the Pump(5kWp-5HP).

(ii) Capacity of the solar PV system is twice the capacity of the Pump(10kWp-5HP).

2.3 Estimation of energy required by the pump

The hydraulic energy required, $E_{h,m}$ can be estimated by using Eq. (3)

$$E_{h,m} = 0.002725\, H\, W_{r,m} \text{ kWh/day}, \qquad (3)$$

Where,
H = Total hydraulic head in meter

2.4 Estimation of array output energy, load energy, and excess energy

The concept of utilizability [15] is used to estimate the array output energy, load energy, and excess energy. The utilizability factor, Ø determines the values of these parameters. PV array output energy, $E_{i,m}$ is given by Eq. (4).

$$E_{i,m} = A_{pv} I_{t,m} \eta_{i,m} \text{ kWh} \qquad (4)$$

Where,
A_{PV} = Area of photovoltaic array in m^2
$\eta_{i,m}$ = Maximum Power Point Tracking System efficiency (fraction)
$I_{t,m}$ = Monthly average hourly solar insolation on tilted surface in kW/m^2

Load energy, $E_{l,m}$ is given by Eq. (5).

$$E_{l,m} = (1 - Ø_m)\, E_{i,m} \quad \text{kWh} \qquad (5)$$

Where,
$Ø_m$ = Monthly average hourly utilizability factor

and, the excess energy, $E_{ex,m}$ that can be supplied to the grid is given by Eq. (6).

$$E_{ex,m} = (Ø_m)\, E_{i,m} \text{ kWh} \qquad (6)$$

2.5 Economic Analysis

The sum of all the following costs gives the system LCC over a period of 20 years [15].

Therefore, the LCC can be given by Eq. (7).

$$LCC = C_{ini} + C_{loan} + C_{O\&M} + C_{rep} \qquad (7)$$

In the above equation, C_{ini} is the initial capital investment or down payment.

The pay back amount towards loan can be obtained by using Eq. (8).

$$C_{loan} = A_i \times \text{Loan tenure period in months} \qquad (8)$$

In the above equation, monthly instalment amount [16], $A_i$can be obtained by using Eq. (9).

$$A_i = \frac{R \times Amount_{loan}}{\left[1-\left\{\frac{1}{(1+R)^n}\right\}\right]} \quad (9)$$

Where,
R = Rate of interest (fraction)

For the entire life cycle period the operation and maintenance cost, $C_{O\&M}$ can be obtained by using Eq. (10a) & Eq. (10b) when this cost for first year, $C_{O\&M0}$ is known.

$$C_{O\&M}=C_{O\&M0}\, x\left(\frac{1+e_o}{d-e_o}\right)x\left(1-\left(\frac{1+e_o}{1+d}\right)^N\right), \text{ if } d\neq e_o \quad (10a)$$

$$C_{O\&M}=C_{O\&M0}\, N, \quad \text{if } d=e_o \quad (10b)$$

Where,
e_o = Rate of inflation/escalation (fraction)
d = Rate of discount (fraction)
N = Life cycle period of the system

Then, the replacement cost, C_{rep} can be obtained by using Eq. (11) when the current component cost, C_u is known.

$$C_{rep}= C_u \sum_{j=1}^{l}\left(\frac{1+e_o}{1+d}\right)^{Nj/l+1}, \quad (11)$$

Where,
l = Number of replacements of the equipment for the life cycle period.

The LCS can be obtained using Eq. (12a), Eq. (12b), and Eq. (12c) when the saving for the first year, S_o is known.

$$LCS = S_o\left(\frac{1+e_o}{d-e_o}\right)\times\left(1-\left(\frac{1+e_o}{1+d}\right)^N\right), \quad \text{if } d \neq e_o \quad (12a)$$

$$LCS = S_o N, \quad \text{if } d = e_o \quad (12b)$$

Total Life Cycle Cost,

$$LCC_{tot}=LCC-LCS \quad (12c)$$

Cost of the energy per unit or LEC (Levelized Energy Cost) can be obtained by using Eq. (13).

$$LEC= \frac{LCCtot}{\text{Energy prduced in total life cycle time}} \quad (13)$$

3. Results and Discussion

Using the methodology explained above, the benefits of grid-connected solar pumps are evaluated in this work. For demonstration of results, Rajanagaarm (Latitude angle of 17.08° N and Longitude angle of 82°E), a rural location in Andhra Pradesh, is chosen where in a 5HP pump is used for cultivating the paddy in one acre. Two different scenarios, based on the options given in the original scheme document published in the website [11] have been evaluated for quantifying the benefits. Under each scenario, there are two cases. The details are as given under:

Scenario-I: Grid power cannotbe permitted for running the pump
Scenario-II: Grid power can be used for running the pump

Under each scenario, there are two cases depending on the capacity of the Solar PV system.

Case-1 Capacity of the Solar PV system is same as the capacity of the Pump
Case-2 Capacity of the Solar PV system is twice the capacity of the Pump.

3.1 Estimation of Water required

The water required for one acre of paddy in the given location is estimated using Eq. (2) and Table 2 presents daily average monthly requirement. The water required during May and November is zero as crop holiday period. The annual average daily water required for one acre of paddy at Rajanagaram is 15.6 m^3.

3.2 Estimation of energy required by the pump

The energy required by the 5HP pump to supply water required for the crop in kWh at a head of 55 m is calculated using Eq. (3) and given in Table 2. Annual average daily hydraulic energy required for pumping 15.6 m^3 of water for one acre of paddy is 2.32 kWh.

Table 2. Monthly Average daily water requirement.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$W_{r,m}$ (m^3/day/acre)	14.1	18.4	20.2	16.8	0	17.4	13.5	14.8	13.6	1.6	0	14.5
$E_{h,m}$(kWh/day)	2.1	2.8	3.0	2.5	0	2.6	2.0	2.2	2.1	1.7	0	2.2

Table 3. Parameter values used in the Economic Analysis.

Parameter	Value	Parameter	Value
Cost of PV System	Rs.60,000 per kWp	O & M Cost (Fixed)	Rs.400 /kWp per annum
Govt. Subsidy	60% (Central and State)	Replacement cost of Inverter (Life: 10 Years)	Rs.10,000 per kVA
Investment by the farmer	10%	Replacement Cost of Motor(5HP) (Life: 10 Years)	Rs.50,000
Loan eligibility	30%	Inflation Rate	5%
Loan Interest Rate	12%	Discount Rate	10%
Tenure	6 Years	Energy Sell Rate	Rs.5 per kWh
Life-Time Period	20 Years	Energy Buy Rate	Rs.6 per kWh

3.3 Estimation of array output energy, load energy, and excess energy

The energy generated by Solar PV system and the excess fed to the gridare obtained based on from Eq. (4) to Eq. (6). The monthly average daily values are shown in the Figure 1, Figure 2 and Figure 3. The efficiency of Solar PV modules is assumed to be 16%.

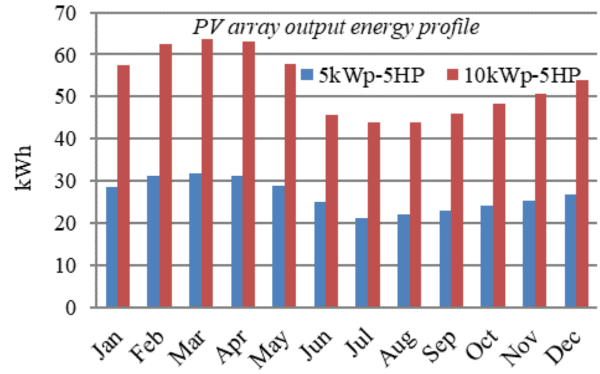

Figure1. PV Array Output energy profile.

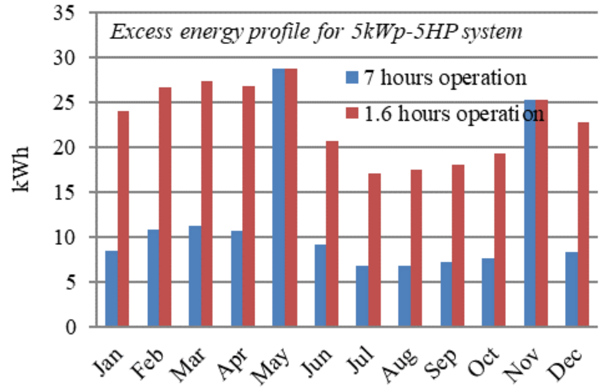

Figure 2. Excess Energy profile for 5kWp – 5HP System.

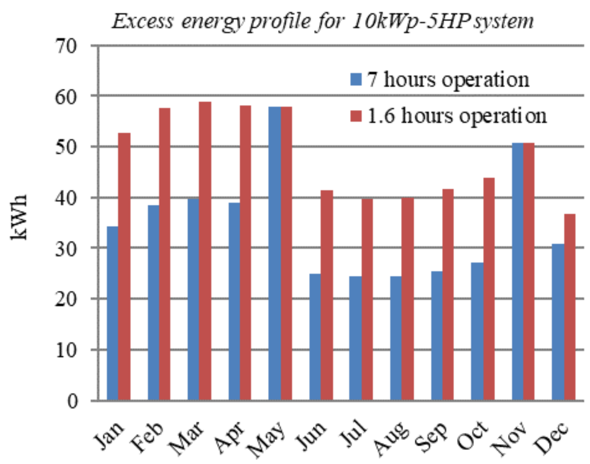

Figure 3. Excess energy profile for 10kWp-5HP system.

3.4 Economic Analysis

The primary objective of the economic analysis in this work is to estimate the additional income to the farmer through selling of excess energy fed to the grid. In addition, LEC is also obtained using the equations from Eq. (8) to Eq. (13). Table 3 gives the important parameters considered in the economic analysis which are adapted from reference [4] for comparison and validation.

Scenario-I: In this scenario, grid power will not be allowed to run the pump. Two case studies are discussed in this scenario. The capacity of the Solar PV system is same as the capacity of the pump is represented as Case-1. The capacity of the Solar PV system is twice that of the pump in Case-2. The rating of the pump considered in this work is 5HP for validating the results with the published work in the literature. The results are presented in Table 4 giving both technical and economical parameters. The first row of Table 4 shows that the pump runs for 7 hours in a day discharging 68.3 m^3/day on an average. The average excess energy delivered per day to the grid is 11.77 kWh. As per the policy document, the scheme is meant for small and marginal farmers whose land holding is about one acre. In such case, the excess water drawn will be wasted resulting in the unnecessary over exploitation of ground water. Hence, to save the water and increase the revenue to the farmer, the pump is run only for 1.6 hours. The results are presented in the second row of Table 4. The water discharged is sufficient for wetting one acre of paddy. The average excess energy generated is 22.8 kWh per day which increases the revenue to the farmer by 193% compared to 7hours of operation for a 5kWp system and the pay-back period is 3.5 years. Similarly, for a 10kWp system with 1.6 hours of operation, excess energy and pay-back period are 48.31 kWh and 3.3 years, respectively.

Scenario–II: In this scenario, the farmer can consume power from the grid. Both the cases are evaluated, and the results are presented in Table 5. The first row of Table 5 shows that the pump runs for 7 hours in a day discharging 68.3m^3/day on an average. The average excess energy delivered per day to the grid is 10.63 kWh. As per the policy document, the scheme is meant for small and marginal farmers whose land holding is about one acre. In such case, the excess water drawn will be wasted resulting in the over exploitation of ground water. Hence, to save the water and increase the revenue to the farmer, the pump is run only for 1.6 hours. The amount of water saved in Case-1 is 15,819 m^3per annum and 20,517 m^3 per annum in Case-2. The results are presented in the second row of Table 5. The water discharged is sufficient for wetting one acre of paddy. The average excess energy generated is 20.18 kWh per day which increases the revenue to the farmer by 190% compared to 7hours of operation for a 5kWp system and the pay-back period is 3.9 years. Similarly, for a 10kWp system with 1.6 hours of operation, excess energy and pay-back period are 41.67 kWh and 3.8 years, respectively.

From the above results, it is evident that in both the scenarios running the pump for 1.6 hoursis beneficial to the farmer giving him good revenue and also saving the water. For checking the consistency of the result, the authors wanted to compare with similar investigation. There is limited work in the literature, particular in the context of the scheme proposed by Government of India.

Table 4. Techno-economic performance of 5HP pump when grid power can't be used for running the pump.

Pumping system	Pump operating time	Water discharge (m^3/day)	Extent of Land (in Acre)	PV array output (kWh)	Excess energy (kWh)	Load energy (kWh)	Pay-back period (Years)
5kWp-5HP	7 hours	68.31	4.38	26.61	11.77	14.85	6.8
(Case-1)	1.6 hours	15.58	1	26.61	22.80	3.74	3.5
10kWp-5HP	7 hours	82.77	5.31	53.05	34.75	18.30	4.6
(Case-2)	1.6 hours	15.58	1	53.05	48.31	3.74	3.3

Note: All parameters are daily average values.

Table 5. Techno-economic performance of 5HP pump when grid power can be used for running the pump.

Pumping system	Pump operating time	Water discharge (m^3)	Land extent (Acres)	PV array output (kWh)	Excess energy (kWh)	Load energy (kWh)	Pay-back Period (Years)
5kWp-5HP(Case-1)	7 hours	68.31	4.38	23.01	10.63	14.85	7.5
	1.6 hours	15.58	1	23.01	20.18	3.74	3.9
10kWp-5HP(Case-2)	7 hours	82..77	5.31	45.73	30..68	18.30	5.2
	1.6 hours	15.58	1	45.73	41.67	3.74	3.8

Note: All parameters are daily average values.

Table 6. Comparison of the result.

S.No	Parameters (Per year)	5kWp-5HP (Reference paper)	5kWp-5HP (Scenario – 1) Present work	5kWp-5HP (Scenario – 2) Present work
1	Peak sunshine hours considered	2,500	2,100	2,100
2	PV Energy, kWh	7,500	7,983	6,903
3	Excess Energy supplied to the grid, kWh	3,750	6,840	6,054
4	Revenue generated to the farmer (Indian Rupees)	18,750	34,200	30,270

However, Shah [4] have published a report and presented the benefits to the farmer in case of him opting for the scheme. Though the work did not mention methodology of evaluation, the present work considers the same technical and economical parameters for comparison. Table 6 gives the comparison of both the works based on the parameters given in the first column of the Table 6. The number of working hours in the proposed work is based on the assumption that Solar Energy is available on an average for 7 hours a day and for 300 days in a year. The revenue generated by the method proposed in the work is Rs.34,200 and Rs.30,270 respectively for scenario-1 and scenario-2 with the selling rate of energy at Rs.5 per kWh. The reasons for increase in revenue in the present work can be attributed to: 1) the pump is allowed to run only for 1.6 hours in a day for supplying the water required for wetting one acre of paddy field; 2) we used the concept of utilizability for accurately assessing the excess energy generated.

4. Conclusions

The present work evaluates the benefits of the grid-connected solar pumps with respect to KUSUM,a scheme offered by Government of India for promoting grid-connected solar water pumps. The work addresses two important issues related to solar energy for agriculture: 1) concerns on over-exploitation of ground water resources and 2) increasing the revenue to the farmer for promoting solar energy. The results show that using solar energy for limited time only for delivering required water and feeding excess energy to the grid is beneficial. It not only addresses the wastage and over-exploitation of ground water but also increases the revenue to the farmer. The present work assumes the weather parameters and financial parameters asconstant. In the future work, the uncertainty of weather and financial parameters will be considered and sensitivity analysis will be carried out for their impact on the outcomes. The methods proposed could be used by DISCOMs for evaluating the benefits depending on the location or crop for prioritising the allocation of scheme to individuals for maximizing the benefits to the farmer, utility and country at large leading to a win-win situation for all stakeholders.

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