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CDM potential of SPV pumps in India

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Abstract

So far, the cumulative number of renewable energy systems such as solar photovoltaic (SPV) irrigation pumps in the agriculture sector in India is far below their theoretical potential despite government subsidy programmes. One of the major barriers is the high costs of investments in these systems.

The clean development mechanism (CDM) provides industrialized countries with an incentive to invest in emission reduction projects in developing countries to achieve a reduction in CO_2 emissions at lowest cost that also promotes sustainable development in the host country. SPV pumps could be of interest under the CDM because they directly displace greenhouse gas emissions while contributing to sustainable rural development. However, there is only one SPV project under the CDM so far.

This study assesses the maximum theoretical as well as the realistically achievable CDM potential of SPV pumps in India. Due to mitigation costs of 24–242 € per ton CO_2 at current CER prices of less than 15 €, SPV pump projects are not viable. However, substitution of diesel pumps could be made viable by a relatively limited subsidy. While the maximum mitigation volume is more than 214 million ton CO_2 on an annual basis, an estimate of achievable CER levels is done using the past diffusion trends of SPV pumps. We find that annual CER volumes could reach 50,000–100,000 by 2012 and 0.25–0.75 million by 2020. This would require that the government sets the subsidy level for SPV pumps at a level that allows them to become viable with the CER revenue. From a macro-economic point of view this makes sense if the sustainability benefits are deemed sufficiently high to warrant promotion of this project type.

Keywords: Clean development mechanism; Agriculture; Renewable energy; CO_2 emissions; Solar photovoltaic pumps; India

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1. Introduction

Ground water is a major source for irrigation and drinking water supply in India. The present contribution of groundwater to irrigation is about 50% in terms of area whereas 80% of the rural domestic water supply is met with ground water [1]. The total replenishable ground water resources in the country have been estimated at 45.2 million-hectare meters per year [2]. At present, the level of ground water exploitation is about 30% of the existing potential. It has been estimated that out of the total precipitation of around 400 million-hectare meters in the country, the surface water availability is about 178 million-hectare meters. Out of this only about 50% can be put to beneficial use because of topographical and other constraints (http://www.saciwaters.org). In rural India, most of the ground water used for domestic consumption is lifted by human power. For irrigation purposes, however, only 40% of the water is lifted by traditional means (i.e. human/animal power) and the rest is lifted by diesel and electric pumpsets [3].

Irrigation water pumping is the second most important direct commercial energy end use in Indian agriculture after land preparation [4]. There are reportedly more than 15 million electric and 6 million diesel irrigation pumpsets in operation (www.incg.org.in). The electricity consumption in the agriculture sector amounts to 27% of total consumption of electricity of 317 TW h in the country during 2000–2001 [5]. Due to the low quality of grid electricity supply, pumpsets are oversized to avoid burnout due to voltage and frequency fluctuations and to achieve enough water flow during the short periods of electricity availability due to heavy subsidies. Many farmers receive their electricity completely free.

Erratic supply of conventional sources of energy and concern for the environment and sustainable development has provided renewed thrust to the development and dissemination of renewable energy-driven pumpsets. Renewable energy options for water pumping include solar photovoltaic (SPV) pumps, windmill pumps and dual-fuel engine pumps using biogas or producer gas. Out of the four renewable energy technologies for irrigation water pumping SPV theoretically has an advantage in meeting the needs of remote communities because of the high distribution costs of grid-power to this market [6] and the competitive position with respect to diesel has improved with the recent oil shock. However, dissemination of SPV pumpsets has proven to be an uphill battle.

A surface pump powered with a 1.8 kW_p[1] photovoltaic (PV) array can deliver about 140,000 litre of water on a clear sunny day from a total head of 10 m. This quantity of water drawn has been found to meet the irrigation requirement of 5–8 acres of land by using improved techniques for water distribution [7]. SPV water pumps are also being used for lifting the water from deep wells for drinking requirements of the people and livestock in unelectrified remote villages, where availability of power is erratic.

The clean development mechanism (CDM) of the Kyoto Protocol has been set up to assist developing countries (Non-Annex-I) in achieving sustainable development by promoting greenhouse gas emission reduction projects that generate emission credits (certified emissions reductions, CERs) for industrialized countries (Annex-I). Small-scale renewable energy projects have significant local environmental and socio-economic benefits. However, due to the small CER volumes generated, such projects may not be able to cover their transactions costs, even under the simplified modalities and procedures developed by the CDM Executive Board.

Could SPV pumps become relevant for the CDM? Theoretically yes, because they directly displace greenhouse gas emissions while contributing to sustainable rural development. We assess the theoretical CDM potential of SPV pumps in India before discussing whether at the current market situation such projects could become attractive.

The paper is set out as follows. Section 2 provides some salient features of the Indian program on SPV pumping. A brief detail of a SPV pump is given in Section 3. The discussion how the CDM could mobilize SPV pumps and the estimation of the CDM potential of SPV pumps is discussed in Sections 4 and 5, respectively. Section 6 presents a method for the estimation of the potential number of SPV pumps. Section 7 presents the forecast diffusion levels of SPV pumps under an optimistic CDM and business-as-usual scenario (BAU). Section 8 summarizes the findings of the study.

2. Program on SPV water pumping in India

The Ministry of Non-conventional Energy Sources of the Government of India initiated a program for the deployment of SPV water pumping systems during 1993–1994. The program is being implemented through Indian Renewable Energy Development Agency (IREDA) and also through the State Nodal Agencies (SNAs). The target was installation of 50,000 SPV water-pumping systems over a period of 5 years [8]. However, till December 2004, only 6780 SPV systems for water pumping had reportedly been installed [7], for the time path see Fig. 1.

The key barrier to the large-scale dissemination of SPV water pumps is the high capital cost of these systems to the farmers compared to the conventional pumps. As farmers do not face the real costs of operating the conventional pumps, their incentive to switch to

[1]PV modules are rated in peak Watts (W_p). This is the maximum power output from the module at a cell temperature of 25 °C and a solar irradiance of 1 kW/m^2. The actual power obtained from the system in the field is generally less than the rated power because (i) the efficiency of a solar cell decreases as its temperature increases and cells in the field may often operate at temperatures higher than 25 °C in tropical areas, (ii) the solar irradiance is usually less than 1 kW/m^2, (iii) imperfect matching of the load may cause the module to operate at a voltage and current that gives a power output less than the maximum, (iv) the pumping system may not be operational at times when irrigation is not required, and (v) downtime required for repair and maintenance, etc. In fact the average output over the daylight hours may be much less than the rated output, even in a location with high average daily solar irradiation, thus resulting in a low capacity utilization of the SPV pump.

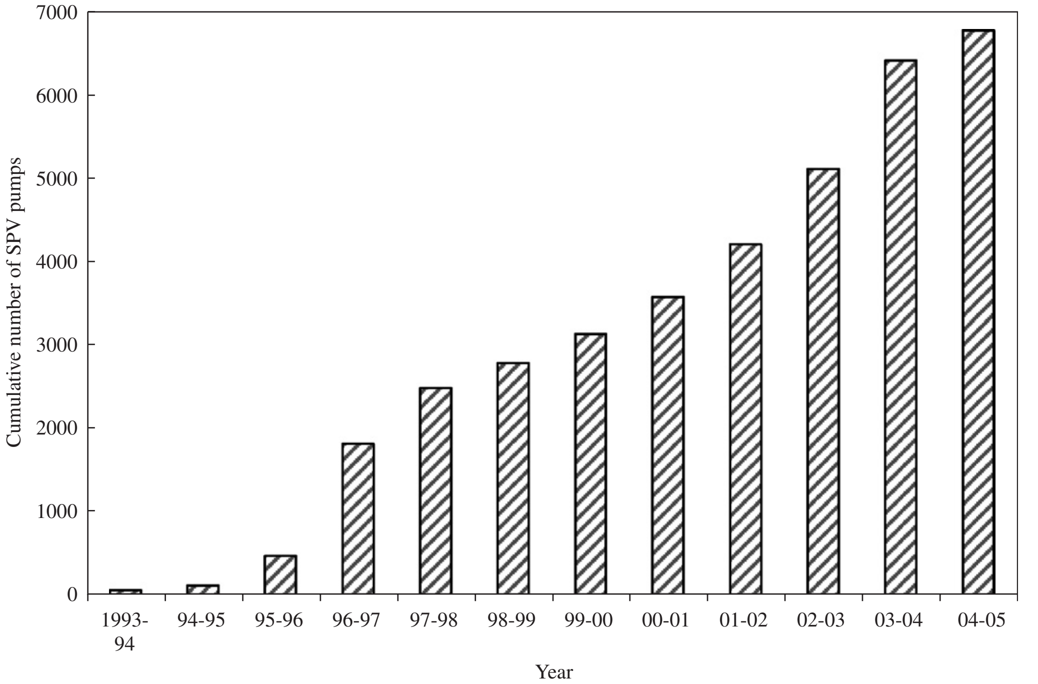

Fig. 1. Cumulative number of installation of SPV pumps in India.

SPV pumps is minimal. While for solar pumping system being promoted through IREDA a package of capital and interest subsidy is available to the user, only a capital subsidy (at slightly higher rate) but no interest subsidy is made available for solar pumps being promoted through SNAs.

In the year 2003–2004, the Ministry initially provided a subsidy to users of SPV water pumping systems of Rs. 110 per W_p[2] of the PV array used with the water pumping system until a maximum of Rs. 0.25 million per system; later reduced to Rs. 75/0.2 million, respectively. Soft loans at 5% per annum for the users directly from IREDA and 2.5% from the financial intermediaries was also made available. Under the program administered by the State agencies, the subsidy was Rs. 135 per W_p of PV array used, later reduced to Rs. 100. The subsidy reductions anticipated a substantial decrease in the cost of SPV pumps, which was based on the cost details given by the SNAs.

The main reason for the slow uptake shown in Fig. 1, which remains far below the 50,000 pump targets, is that despite the subsidy there remains a substantial gap in investment cost between SPV pump and diesel/electric pump of more than Rs. 0.1 million per system. If farmers get free electricity, they have no incentive to switch. For diesel pumpsets, there may be an incentive but it depends on the accesssibility of the subsidies. Transaction costs to get an allocation of a subsidy may include bribing officials and preparing paperwork.

[2] 55 Indian Rupees equals 1 €.

3. SPV water pump

A SPV water pumping system (Fig. 2) consists of a PV array, motor-pump and a power conditioning equipment (optional). Provision for storage of electricity is not provided in these systems. Instead, if desired, a provision can be made for water storage, which may be more cost effective than having a storage battery. The power conditioning equipment is used to stabilize the fluctuating electrical energy output of the array. Depending upon the total dynamic head and the required flow rate of water, the pumping system can be surface or submersible type and the motor can be either AC or DC. For AC pumping systems an inverter is also required [9].

4. How the CDM could be applied to the diffusion of SPV pumps

Small-scale renewable energy and energy efficiency projects are helping to meet the needs of rural people in developing countries, alleviating poverty and fostering sustainable development. However, the low emission reductions per installation are making it difficult for such projects to derive value from participating in the CDM. Negotiators of the Marrakesh Accords of November, 2001 [10] as well as the CDM Executive Board recognized this problem and adopted simplified CDM modalities and procedures for qualifying small-scale projects defined as

- renewable energy project activities with a maximum output capacity equivalent of up to 15 MW,
- energy efficiency improvement project activities which reduce energy consumption by up to the equivalent of 15 GW h per year,
- other project activities that both reduce anthropogenic emissions by sources and directly emit less than 15 kt CO_2 per year.

However, the current design of the CDM is resulting in high transactions costs to individual small-scale projects [11] even with the simplified rules. Costs can be reduced by bundling similar small projects into a single project that is still eligible for the simplified procedures. Michaelowa et al. [12] reported that projects which generate less than 10,000 CERs per year will not be viable. However, the "gold rush" atmosphere of 2005 has also mobilized small-scale project developers. Fig. 3 shows the number of different project size categories of the 402 CDM projects submitted until November 3, 2005. Out of the 402 CDM projects, so far only one involves SPV systems—a large-scale dissemination program of solar home systems in Morocco. This shows that current market prices have not been able to mobilize SPV technologies so far.

4.1. Baseline

The 'reference case' is the energy supply scenario used to define the baseline[3] situation for calculating the GHG emissions that would be expected in the absence of the

[3]The quantification of climate benefits of a project—i.e. the mitigation of GHG emissions—is done by means of a "baseline". A baseline describes the (theoretical) emissions that would have occurred in case the CDM project was not implemented. The amount of CERs that can be earned by the project are then calculated as the difference of baseline emissions and project emissions.

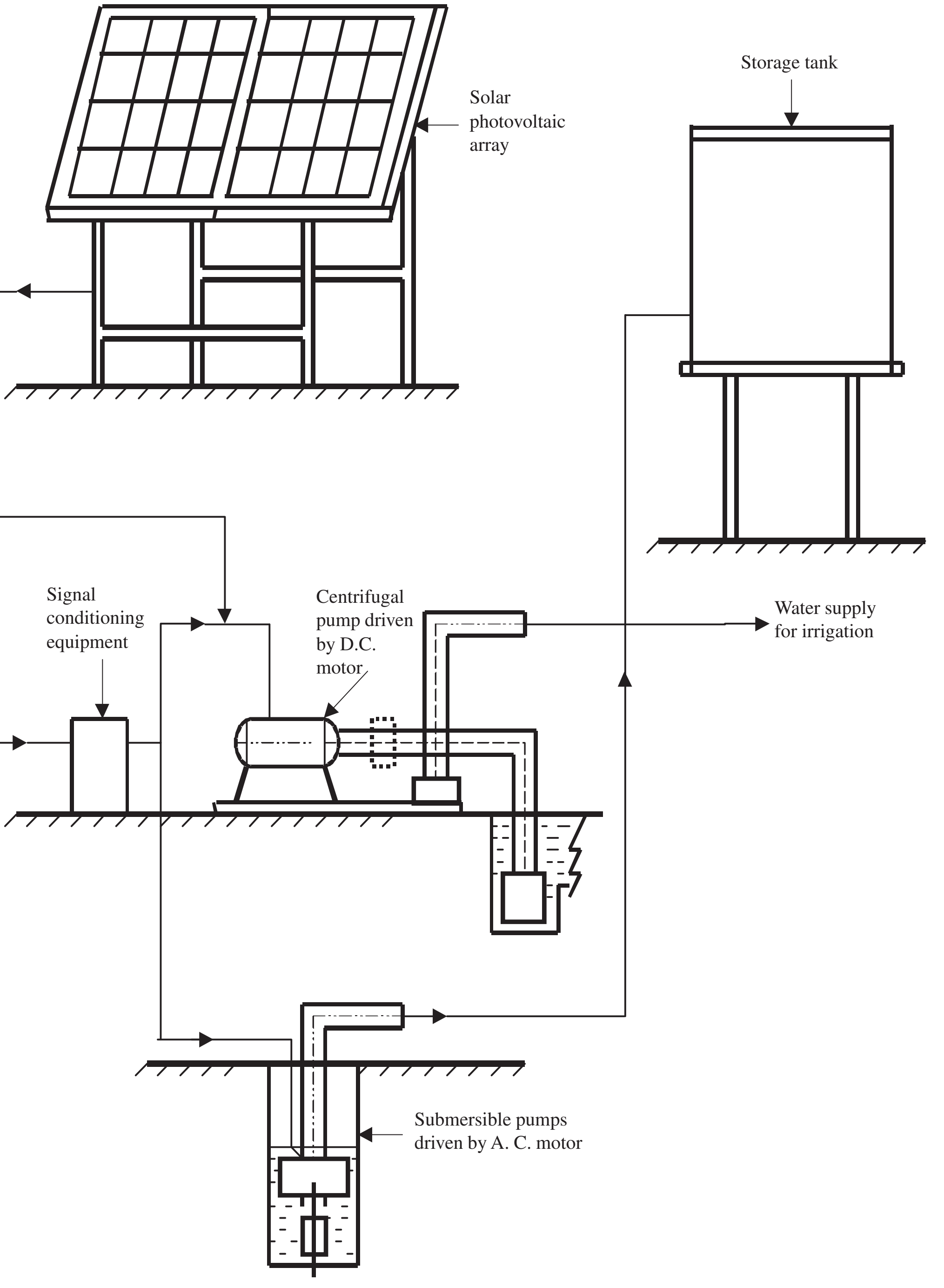

Fig. 2. Schematic diagram of solar photovoltaic water pump.

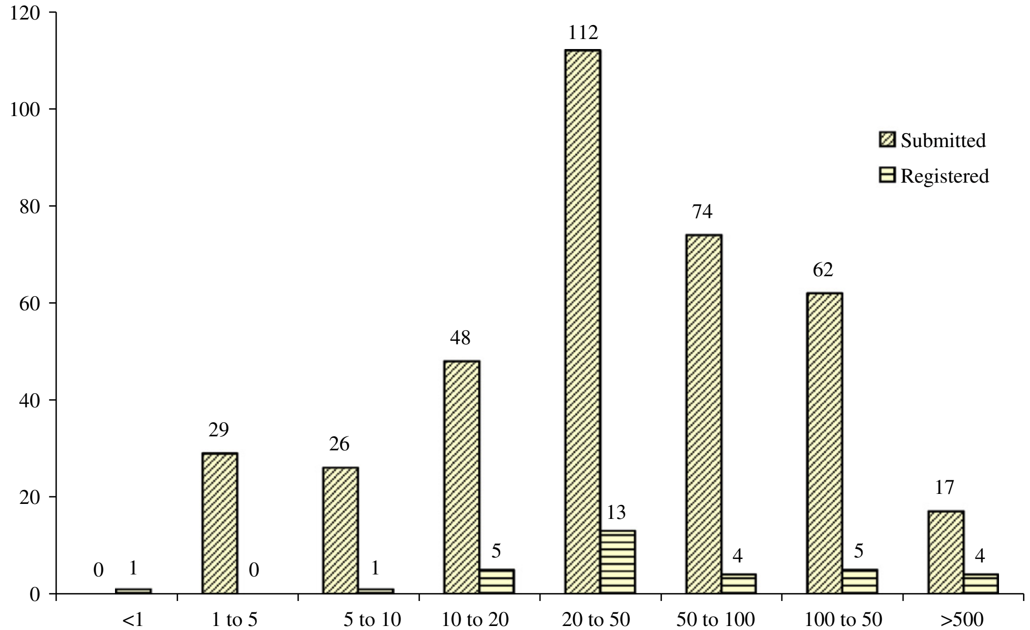

Fig. 3. Size categories of submitted and registered CDM projects (average 1000 CERs p.a. until end of 2012).

installation of SPV pumps. The selection of the reference case will have a big impact on the amount of emission reductions that can be credited to the installation of SPV pumps. The CO_2 emissions mitigation benefit associated with an SPV water pumping system depend upon the type/amount of fuel saved. An SPV water pumping system usually replaces either diesel or electricity. To estimate the CDM potential of SPV pumps in the country the small-scale methodology I.A "Electricity generation by the user" in its version of 30 September 2005 [13] has been used which explicitly mentions water pumps for irrigation. It allows the following options to calculate the energy baseline:

$$EB_{\text{kW h/year}} = \sum_i (n_i \cdot c_i) \cdot (1 - l) \tag{1}$$

with $\sum_i$ represents the sum of installed SPV pumps, n_i the number of farmers supplied by the SPV pumps, c_i the estimate of average annual individual consumption (kW h per year) observed in closest grid electricity systems among rural grid connected farmers, and l the percentage of average technical distribution losses that would have been observed in diesel powered mini-grids installed by public programmes or distribution companies in isolated areas. This option is cumbersome as one would have to make surveys of grid-connected farmers' electricity use. It is therefore not used in the estimation.

$$EB_{\text{kW h/year}} = \frac{\sum_i O_i}{1 - l} \tag{2}$$

with $\sum_i$ and l defined as in Eq. (1) and O_i being the estimated annual electricity output of the SPV pumps. This option will be used in the remainder of the paper for replacement of electric pumpsets. For the emissions factor per kW h, a default of 900 g CO_2/kW h can be used but higher factors are also possible if justified.

Trend adjusted projection of historic fuel consumption of replaced pumps. This would obviously only be relevant for diesel-fuelled pumpsets and is retained for that case.

4.2. Additionality

To maintain the environmental integrity of the Kyoto Protocol, CDM credits are given only for activities that would otherwise not be expected to occur. Even in the hypothetical case an off-grid situation where lifecycle costs of the SPV pump would be cheaper than all other alternatives, the high up-front investment cost to a farmer in acquiring a SPV pump would still be a high barrier to widespread market penetration. None of the SPV pumps so far disseminated in India has been sold without a subsidy. In terms of costs per kW h in grid-connected areas, costs of SPV pumps will be higher than grid electricity by an order of magnitude and projects thus are additional at any rate.

4.3. Monitoring

Monitoring under small-scale rules consists in an annual check of all systems or a sample thereof to ensure that they are still operating. Since the installations of SPV pumps are often widely dispersed in sparsely populated and difficult to reach areas, monitoring costs could make CDM participation prohibitive if each farmer with a system is visited. Simple and efficient sampling procedures are therefore required. There are two variables that need to be monitored and verified in order to correctly establish emission reductions from SPV pumps according to small-scale methodology I.A.: number of systems operational in the field, and estimated fuel savings per available system.

5. CDM potential of SPV pumps in India

The amount of CO_2 emissions saved by a SPV pump would essentially depend upon the amount(s) of fuel(s) saved by its use, which, in turn, depend upon the annual useful energy provided by the SPV pump and the efficiency of utilization of the fuel in the existing pump. Owing to differences in efficiencies of utilization of fuel and other input parameters for diesel and electric pumps, the CO_2 emissions mitigation potential would be different for the cases of diesel and electricity substitution.

In case of diesel substitution, i.e. option 3 of the methodology, the gross annual CO_2 emissions reduced by a SPV pump, $GCE_{spv,d}$, can be estimated as

$$GCE_{spv,d} = \left(\frac{44}{12}\right)\left\{\frac{8760 CUF_{spv} P_{spv} \eta_{p,spv} SF_d}{0.746 \eta_{dep}}\right\} CEF_d f_d, \tag{3}$$

where P_{spv} (in kW_p) represents the capacity of SPV system, CUF_{spv} (in fraction) the capacity utilization factor of the SPV pump, $\eta_{p,spv}$ (in fraction) the overall efficiency of SPV water pump, SF_d (in l/bhp h) the specific diesel consumption in the conventional diesel engine pumpset, η_{dep} (in fraction) the overall efficiency of diesel engine pump, CEF_d the carbon emission factor of diesel and f_d the fraction of carbon oxidized during diesel combustion. The term inside the second bracket of the right-hand side of Eq. (3) is the annual amount of diesel saved by an SPV pump.

In case of electricity substitution, the gross annual CO_2 emissions reduced by a SPV pump, $GCE_{spv,e}$ can be estimated as

$$GCE_{spv,e} = 8760\left\{\frac{CUF_{spv}P_{spv}\eta_{p,spv}}{\eta_{emp}(1-l)}\right\}CEF_e, \tag{4}$$

where CEF_e (in kg CO_2/kW h) represents the CO_2 emission factor for electricity, and l (in fraction) the electrical transmission and distribution losses of the grid. The term inside the bracket in the right-hand side of the above equation is the annual amount of grid electricity[4] saved by the SPV pump.

With respect to CEF_e the range of regional grid average emissions factors in India ranges from 380 g CO_2/kW h in the north-eastern grid to 1190 g CO_2/kW h in the Eastern grid [14]. Thus, choosing the 900 g CO_2/kW h default factor makes sense for all grids whose average emission factor is below that level which is the case for all grids except the Eastern. The CDM Executive Board should not have a reason to reject higher regional grid factors, particularly as regional grids have been defined as the relevant grid for large-scale renewable electricity methodologies.

What is now the financial attractiveness of a SPV pump CDM project? The monetary benefits associated with an SPV water pumping system depend upon the monetary value of electricity/fuel saved which are the product of annual fuel savings and the price of the fuel/electricity saved and the difference in investment costs between the common electric/diesel pump and the SPV pump. Here, one has to differentiate between the price the farmer would pay (which is zero in the case of electricity) and the cost of providing the electricity/fuel incurred by the State Electricity Board.

The monetary value of the annual diesel saved (MV_{ds}) by the SPV pump can be expressed as

$$MV_{ds} = 8760\left[\frac{CUF_{spv}P_{spv}SF_d\eta_{p,spv}}{0.746\eta_{dep}}\right]p_d, \tag{5}$$

where p_d represents the market price of diesel (in Rs./l).

Similarly, the monetary value of the annual electricity saved (MV_{es}) by the SPV pump can be expressed as

$$MV_{es} = 8760\left[\frac{CUF_{spv}P_{spv}\eta_{p,spv}}{\eta_{emp}}\right]p_e, \tag{6}$$

where p_e represents the market price of electricity (in Rs./kW h).

The difference between the cumulative present value of the benefits (due to the substitution of the commercial fuels and the avoided costs of annual repair and maintenance as well as of diesel/electric pump replacement at the end of its technical lifetime, if this ends before the end of technical lifetime of the SPV pump) and the costs (i.e. capital cost and annual repair and maintenance cost) is the net present value (NPV) of the investment on the SPV pump. Therefore, in case of diesel replacement, the present value of

[4] We do not want to earn credit by the oversizing of the diesel/electric pumps compared to the SPV pumps installed by the CDM project activity. However, the energy value taken into account is the electricity output.

net benefits (NPV_d) of an investment in the SPV water pumping system can be expressed as

$$\mathrm{NPV_d} = \left[(\mathrm{MV_{ds}} - (\mathrm{CM_{spv}} - \mathrm{CM_d}))\left\{\frac{(1+d)^{t_{spv}} - 1}{d(1+d)^{t_{spv}}}\right\} - C_o + \left\{\frac{C_{dnew,T}}{(1+d)^T}\right\}\right], \quad (7)$$

where CM_d represents the annual repair and maintenance cost of diesel pump, CM_{spv} the annual repair and maintenance cost of SPV pump, C_o the capital investment cost of SPV pump, and $C_{dnew,T}$ the cost of new diesel pump to be installed in the Tth year.

Similarly, in the case of substitution of grid electricity, the present value of net benefits (NPV_e) can be expressed as

$$\mathrm{NPV_e} = \left[(\mathrm{MV_e} - (\mathrm{CM_{spv}} - \mathrm{CM_e}))\left\{\frac{(1+d)^{t_{spv}} - 1}{d(1+d)^{t_{spv}}}\right\} - C_o + \left\{\frac{C_{enew,T}}{(1+d)^T}\right\}\right], \quad (8)$$

where CM_e represents the annual repair and maintenance cost of electric pump, and $C_{enew,T}$ the cost of new electric pump to be installed in the Tth year.

The background parameters to calculate Eqs. (7)–(8) are given in Table 1. We observe in Tables 2a and b that under the scenario with current diesel and electricity prices the NPV of an investment in the SPV pump is not attractive, thus showing additionality for the CDM. Only a diesel scenario with higher subsidy would be commercially viable. The break-even prices of CERs would have to be 24–242 €. While the replacement of electric pumpsets would cost more than an order of magnitude more than current CER prices on the world market that lie between 5 and 15 € depending on the quality of the project, the replacement of diesel pumps would only require a relatively limited amount of subsidy to

Table 1
List of input parameters used in financial calculations

Parameter		Symbol	Unit	Value
Annual operation, repair and maintenance cost (as a fraction of capital cost)	SPV pump	CM_{spv}	Fraction	0.01
	Diesel pump	CM_d		0.10
	Electric pump	CM_e		0.02
Capital cost of the system	SPV pump (1.8 kW_p)	C_o	Rs.	295,000
	Diesel pump	$C_{d,new}$		32,000
	Electric pump	$C_{e,new}$		24,000
Capacity utilization factor for the SPV pump		CUF_{spv}	Fraction	0.20
Carbon emission factor for diesel		CEF_d	tC/TJ	20.2
Discount rate		d	Fraction	0.10
Electrical transmission and distribution losses		l	Fraction	0.22
Fraction of carbon oxidized in diesel combustion		f_d	Fraction	0.99
Market price of diesel		p_d	Rs./l	32
Market price of electricity		p_e	Rs./kW h	2.50
Overall efficiency of the diesel engine pump		η_{dep}	Fraction	0.40
Overall efficiency of the electric motor pump		η_{emp}	Fraction	0.52
Overall efficiency of the SPV pumps		η_{spv}	Fraction	0.40
Specific fuel consumption in diesel engine pumpset		SF_d	l/bhp h	0.22
Useful lifetime of the SPV pump		t_{spv}	Years	20
Useful lifetime of diesel engine pump		T	Hours	20,000
Useful lifetime of electric motor pump		T	Hours	20,000

Source: Refs. [9,30,31].

Table 2
Financial attractiveness of an investment on 1.8 kW SPV pumps in India depending on (a) diesel price, subsidy rates and CER revenues and (b) electricity price, subsidy rates and CER revenues

Indicators	Unit	Price of diesel: Rs. 32/l	Price of diesel: Rs. 32/l + 10% subsidy	Price of diesel: Rs. 45/l
(a) Diesel price and subsidies				
Simple payback period	Years	9.38	8.50	6.78
Benefit to cost ratio	—	0.91	1.00	1.26
Net present value (NPV)	Rs.	−27,166	0	75,765
Cost per CER	€	24	—	—
(b) Electricity price and subsidies				
Indicators	Unit	Price of electricity: Rs. 0.00/kW h	Price of electricity: Rs. 2.50/kW h	Price of electricity: Rs. 2.50/kW h + 80% subsidy
Simple payback period	Years	−213	63	8.5
Benefit to cost ratio		0.03	0.20	1.00
Net present value (NPV)	Rs.	−306,775	−255,144	0
Cost per CER	€	242	202	—

make them viable CDM projects. This however, does not include other barriers to project implementation such as the fear of farmers not to receive maintenance in case of breakdown and the unfamiliarity of the PV technology.

6. Potential estimation of SPV pumps in India

The potential of SPV pumps for irrigation depends on several factors, such as resource availability, groundwater requirement and its availability, affordability for farmers, and propensity of the farmers to invest in a SPV pump, etc. [15]. Therefore, the theoretical potential number of SPV pumps, N_{spv}, can be estimated by using the following expression:

$$N_{\text{spv}} = \sum_{j=1}^{5} \left\{ \frac{\text{NSA}_{\text{s}}(1-\xi_{\text{s}})\xi_{\text{g-10}}\xi_{\text{lh},j}}{\zeta_j} \right\}, \tag{9}$$

where NSA_{s} represents the net sown area in the state, ξ_{s} the areas in the state with surface water availability (as a fraction of the net sown area in the state), $\xi_{\text{g-10}}$ the area with ground water table up to 10 m (as a fraction of the total area requiring ground water in the state), $\xi_{\text{lh},j}$ the net sown area operated by jth category of farmers (on the basis of land holding size) as a fraction of net sown area in the state ($j = 1, 2, 3, 4$, and 5 correspond to marginal, small, semi-medium, medium, and large, respectively), ζ_j represents the average size of land holding of jth category of farmers in the state.

Table 3 presents the state wide net sown area, its fraction of area under surface irrigation (ξ_{s}) and the area with different ground water table in India (as a fraction of total area requiring ground water) [16–18]. Table 4 presents the statewide average sizes of land

Table 3
State wise net sown area, its fraction irrigated by surface water (ξ_s) and area with different ground water table in India

State	Net sown area (thousand hectare)	ξ_s (fraction)	Area with different ground water table (as a fraction of the total area requiring ground water)	
			Up to 5 m	Up to 10 m
Andhra Pradesh	14,460	0.17	0.32	0.81
Arunachal Pradesh	350	—[a]	0.44	1.00
Assam	3205	0.11	0.74	0.97
Bihar[b]	10,743	0.11	0.49	0.96
Goa	67	0.10	0.75	1.00
Gujarat	10,292	0.06	0.20	0.56
Haryana	3711	0.37	0.38	0.70
Himachal Pradesh	1010	0.00	0.28	0.61
Karnataka	12,321	0.09	0.22	0.66
Kerala	1796	0.09	0.38	0.82
Madhya Pradesh[c]	22,111	0.09	0.14	0.67
Maharashtra	20,925	0.04	0.21	0.74
Orissa	5296	0.24	0.49	0.95
Punjab	4033	0.34	0.34	0.75
Rajasthan	20,971	0.08	0.16	0.40
Tamil Nadu	7474	0.20	0.47	0.84
Uttar Pradesh[d]	17,986	0.18	0.44	0.85
West Bengal	5656	0.17	0.35	0.81

Source: Refs. [16–18].
[a]Negligible area.
[b]Including Jharkhand.
[c]Including Chattisgarh.
[d]Including Uttaranchal.

holding of different categories of farmers in India [18]. The fractional distribution of net sown area among different categories of farmers in various states of India is presented in Table 5 [18]. Other input parameters used in calculations are presented in Table 1.

Sufficient solar radiation is necessary for all devices based on solar energy. It is recommended that for installing SPV pumps, the average daily solar radiation in the least sunny month should be greater than 4 kW h/m^2/day on a horizontal surface [19]. Ideally, detailed solar radiation data for each location should be used in evaluating the potential of using an SPV pump. However, to make an initial macro-level assessment, broad solar radiation availability characteristics readily available in the literature are used [20]. On a macro-level, seven north-eastern states and the northern states of Jammu and Kashmir, Himachal Pradesh and Uttranchal in India can be given low priority in the process of identification of niche areas for installation of SPV pumps.

Since surface water irrigation is usually the cheapest option for irrigation [21], farmers having access to sufficient surface water for irrigation may not need any other option(s). Therefore, the areas in the country with surface water availability (a fraction ξ_s of the net sown area) have not been included in the potential estimation [17,18,22]. It is assumed that

Table 4
State wise average sizes of land holdings of different categories of farmers (for the year 1990–91)

State	Marginal farmers (ha)	Small farmers (ha)	Semi-medium farmers (ha)	Medium farmers (ha)	Large farmers (ha)
Andhra Pradesh	0.45	1.43	2.71	5.86	15.66
Arunachal Pradesh	0.63	1.53	2.80	5.65	16.40
Assam	0.40	1.40	2.68	5.18	80.80
Bihar[a]	0.35	1.36	2.73	5.65	16.41
Goa	0.33	1.54	2.25	4.50	19.00
Gujarat	0.53	1.47	2.83	5.99	16.45
Haryana	0.47	1.52	2.81	5.86	15.41
Himachal Pradesh	0.40	1.42	2.74	5.69	16.17
Karnataka	0.47	1.46	2.75	5.93	15.28
Kerala	0.17	1.37	2.60	5.43	59.33
Madhya Pradesh[b]	0.45	1.45	2.78	6.04	16.44
Maharashtra	0.49	1.46	2.77	5.86	15.13
Orissa	0.49	1.38	2.63	5.40	16.80
Punjab	0.55	1.61	2.91	6.21	16.07
Rajasthan	0.48	1.44	2.85	6.23	19.11
Tamil Nadu	0.36	1.41	2.73	5.71	18.52
Uttar Pradesh[c]	0.38	1.41	2.73	5.55	15.42
West Bengal	0.44	1.53	2.78	5.39	203.00
All India average	0.39	1.43	2.76	5.90	17.33

Source: Ref. [18].
[a]Including Jharkhand.
[b]Including Chattisgarh.
[c]Including Uttaranchal.

the surface water, wherever available, is sufficient to meet the irrigation water requirement. Furthermore, only those areas with groundwater requirement (as a fraction of the total areas requiring ground water) have been considered where the ground water table [16] is within a pre-specific depth. A centrifugal surface pump coupled with an SPV array is usually considered for shallow well water pumping. The maximum suction head for such a surface pump is reported to be 7 m. SPV systems with a submersible pump are reportedly capable of deep well water pumping up to 70 m [23]. However, such deep well irrigation pumping may not always be economical [24]. As a consequence, SPV water pumping for irrigation is preferably carried out in areas with ground water table less than 10 m.

The Central Ground Water Board (CGWB) monitors the ground water table in India from a network of about 15,000 stations. Measurements of ground water tables are taken at these stations four times in a year. It is observed that during the pre-monsoon period (May month) with maximum irrigation water demand the ground water table is deepest [16]. Therefore, the ground water table for the month of May (pre-monsoon period) has been considered in this study [16].

Table 6 presents the estimated potential of SPV pumps for irrigation water pumping in India. The potential number of SPV pumps are estimated at 70 million. With 14 million SPV pumps the state of Uttar Pradesh has the highest utilization potential followed by Bihar (11 million).

Table 5
State wise fractional distribution of net sown area among different categories of farmers in India (for the year 1990–1991)

State	Marginal farmers	Small farmers	Semi-medium farmers	Medium farmers	Large farmers
Andhra Pradesh	0.16	0.20	0.25	0.26	0.13
Arunachal Pradesh	0.03	0.07	0.24	0.42	0.23
Assam	0.19	0.24	0.29	0.15	0.13
Bihar[a]	0.33	0.18	0.24	0.18	0.06
Goa	0.28	0.16	0.13	0.13	0.28
Gujarat	0.05	0.13	0.24	0.39	0.19
Haryana	0.08	0.12	0.25	0.35	0.19
Himachal Pradesh	0.21	0.23	0.26	0.20	0.10
Karnataka	0.09	0.19	0.26	0.31	0.16
Kerala	0.48	0.21	0.14	0.06	0.10
Madhya Pradesh[b]	0.06	0.13	0.22	0.35	0.24
Maharashtra	0.08	0.19	0.28	0.33	0.12
Orissa	0.20	0.27	0.29	0.19	0.05
Punjab	0.04	0.08	0.21	0.40	0.27
Rajasthan	0.03	0.07	0.14	0.30	0.45
Tamil Nadu	0.28	0.24	0.23	0.17	0.08
Uttar Pradesh[c]	0.31	0.24	0.23	0.17	0.04
West Bengal	0.36	0.30	0.23	0.08	0.04
Lakshdweep	1.00	0.00	0.00	0.00	0.00
A & N island	0.04	0.11	0.30	0.33	0.19

Source: Ref. [18].
[a]Including Jharkhand.
[b]Including Chattisgarh.
[c]Including Uttaranchal.

Using Eqs. (3) and (9) the theoretical maximum CO_2 mitigation potential[5] of SPV pumps in case of diesel substitution can be estimated as

$$\mathrm{CDM}_{\mathrm{spv,d}} = 8760\left(\frac{44}{12}\right)\sum_{i=1}^{5}\left[\left(\frac{\mathrm{NSA_s}(1-\xi_s)\xi_{g\text{-}10}\xi_{\mathrm{lh},j}}{\zeta_j}\right)\left\{\frac{\mathrm{CUF_{spv}}P_{\mathrm{spv}}\eta_{\mathrm{p,spv}}\mathrm{SF_d}\mathrm{CEF_d}f_{\mathrm{d}}}{0.46\eta_{\mathrm{dep}}}\right\}\right]. \quad (10)$$

It amounts to 171 million ton CO_2 per year.

Similarly, using Eqs. (4) and (9) the mitigation potential of SPV pumps in case of electricity substitution can be estimated as

$$\mathrm{CDM}_{\mathrm{spv,e}} = 8760\sum_{j=1}^{5}\left[\left(\frac{\mathrm{NSA_s}(1-\xi_s)\xi_{g\text{-}10}\xi_{\mathrm{lh},j}}{\zeta_j}\right)\left\{\frac{\mathrm{CUF_{spv}}P_{\mathrm{spv}}\eta_{\mathrm{p,spv}}\mathrm{CEF_e}}{\eta_{\mathrm{emp}}(1-l)}\right\}\right]. \quad (11)$$

Mitigation levels would be 214 million ton CO_2 per year, taking into account that $\mathrm{CEF_e}$ (in $\mathrm{kg\,CO_2/kW\,h}$) represents the default CO_2 emission factor or the higher emission factor for electricity.

[5]This does not take into account the relation between SPV pump cost and CER price.

Table 6
Theoretical mitigation potential of SPV pumps in India

States	Region	Potential number of SPV pumps (million)	CDM potential (million CER's) with a baseline of 900 g CO_2/kW h	Total capacity (MW_p)	Number of projects[a]
Andhra Pradesh	Southern	6.2	17	11,234	749
Assam	North-eastern	2.2	6	3901	260
Bihar	Eastern	11.1	41[b]	20,068	1338
Goa	Western	0.1	0	116	8
Gujarat	Western	1.8	5	3320	221
Haryana	Northern	0.7	2	1224	82
Karnataka	Southern	3.5	10	6246	416
Kerala	Southern	4.1	12	7442	496
Madhya Pradesh	Western	5.1	14	9188	613
Maharashtra	Western	6.7	19	12,058	804
Orissa	Eastern	2.9	11[b]	5180	345
Punjab	Northern	0.6	2	1010	67
Rajasthan	Northern	1.9	5	3336	222
Tamil Nadu	Southern	5.4	15	9671	645
Uttar Pradesh	Northern	14.0	39	25,230	1682
West Bengal	Eastern	4.2	16[b]	7606	507
All India		70.5	214	126,830	8455

[a]Less than 15 MW.
[b]Baseline 1190 g CO_2/kW h.

Table 6 gives a breakdown according to states. It may be noted that Bihar has the maximum mitigation potential (41 million ton CO_2) followed by Uttar Pradesh (39 million ton CO_2), Maharashtra (19 million ton CO_2), Andhra Pradesh (17 million ton CO_2), etc. The highest mitigation potential in Bihar is due to the high baseline values (i.e. 1190 g CO_2 for the eastern regional grid) used in the caculations. From Table 6 it can be noted that the minimum number of potential CDM projects on SPV pumps in India to benefit from small-scale project rules would have to be about 9000. More than 1600 projects could be installed in Uttar Pradesh alone.

Obviously, given the CER prices needed to make SPV pump projects viable without subsidies, under the current CER price no CDM project would take place. The mitigation scenario set out here could only be reached at CER prices of more than 240 €, which are extremely unlikely. Thus the challenge is now to find out which part of the theoretical potential could be mobilized at probable CER prices and how government would have to contribute. However, even under an ideal government support, technology diffusion is not instantaneous.

7. Diffusion of SPV pumps in India

The diffusion of a technology measured in terms of the cumulative number of adopters usually conforms to an exponential curve [25] as long as the new technologies manage to become competitive with incumbent technologies. Otherwise, the steep section of the curve would never be reached because technology use falls back to zero at the removal of subsidies. The exponential growth pattern may be of three types—(i) simple exponential, (ii) modified exponential, and (iii) S-curve. Out of these three growth patterns, the simple exponential pattern is not applicable for the dissemination of renewable energy technologies, as it would imply infinite growth. The modified exponential pattern (with a finite upper limit) is more reasonable but such a curve may not match the growth pattern in the initial stage of diffusion [26,27]. Empirical studies have shown that in a variety of situations the growth of a technology over time may conform to an S-shaped curve, which is a combination of simple and modified exponential curves. The S-shaped curves are characterized by a slow initial growth, followed by rapid growth after a certain take-off point and then again a slow growth towards a finite upper limit to the dissemination [28]. However, a logistic model is used to estimate the theoretical cumulative number of SPV pumps considered in the study at different time periods assuming that SPV becomes competitive in the future (as for example in the case of a high diesel price).

As per the logistic model, the cumulative number, $N(t)$, of the renewable energy technology disseminated up to a particular period (tth year) can be expressed as [28,29]

$$N(t) = M\left[\frac{e^{(a+bt)}}{1+e^{(a+bt)}}\right], \tag{12}$$

where M represents the estimated maximum utilization potential of the renewable energy technology in the country. The regression coefficients a and b are estimated by a linear

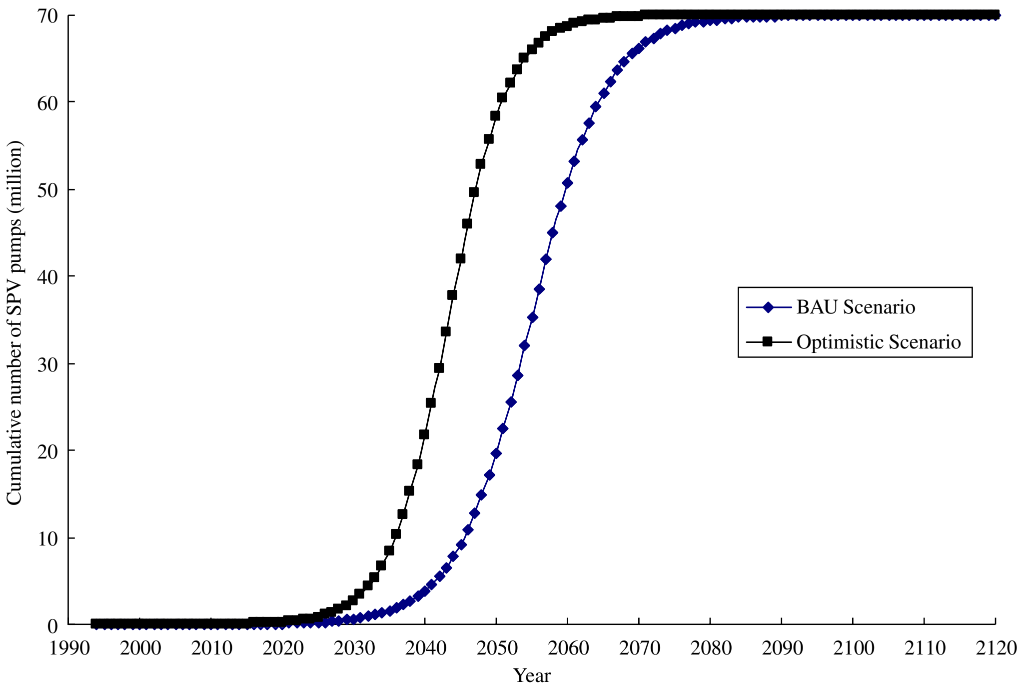

Fig. 4. Time variation of cumulative number of installation of SPV pumps in India using Logistic model.

regression of the log–log form of Eq. (12) as given below

$$\ln\left[\frac{N(t)/M}{1-(N(t)/M)}\right] = a + bt. \qquad (13)$$

Fig. 4 represents the projected time variation of the cumulative number of SPV pumps using the logistic model considered in the study. Two cases such as BAU and optimistic scenario (OS) are presented. The values of the regression coefficients using a logistic model have been estimated by regression of the time series data for the installation of SPV pumps (Fig. 1) extracted from the annual reports of the MNES [7]. In the OS it is assumed that, in

Table 7
Projected values of the cumulative number of SPV pumps and associated CER generation

Year	Projected values of the cumulative number of SPV pumps (0 0 0)		Projected values of the cumulative installed capacity of SPV pumps (MW_p)		Projected values of the annual CER[a] generation (0 0 0)	
	BAU	OS	BAU	OS	BAU	OS
2008	9	14	16	26	26	40
2012	20	37	35	67	55	105
2016	42	98	76	176	118	274
2020	90	255	162	459	252	715

[a]Baseline 900 g CO_2/kW h.

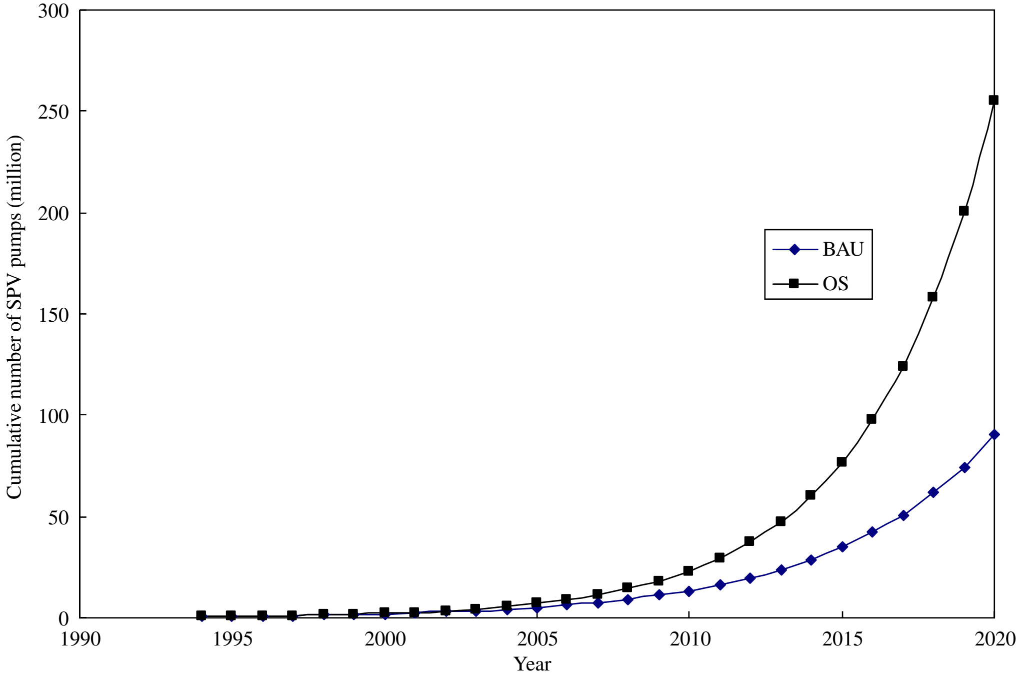

Fig. 5. Realistic CDM potential for SPV pumps until 2020.

the past, if the diffusion of SPV pumps would have been driven by the market forces instead of subsidies then the cumulative number of installation of SPV pumps would be three times more than the actual level. Our results indicate that in India, even with highly favorable assumptions, the dissemination of SPV pumps for irrigation water pumping is not likely to reach its maximum estimated potential in another 100 years. But all these time periods are not relevant for the CDM whose current endpoint is 2012 and which may only be able to live longer if post-2012 negotiations retain an emission target-based policy regime. However, CDM could be used as a tool to foster the dissemination of SPV pumps in the country. It could accelerate the diffusion process.

Table 7 presents the projected values of the cumulative number of SPV pumps and likely CER generation using the logistic model while Fig. 5 shows the development over time. It may be noted that with the current trend of dissemination of SPV pumps in the country around 20,000 SPV pumps could be installed up to the end of first crediting period in the BAU scenario whereas in the OS scenario 37,000 SPV pumps could be installed. Up to the year 2020, more than 76,000 SPV pumps are expected to be installed that would generate 182,000 CERs.

8. Concluding remarks

Our estimates indicate that, there is a vast theoretical potential of CO_2 mitigation by the use of SPV pumps for irrigation water pumping in India. The potential number of SPV pumps are estimated at 70 million. The annual CER potential of SPV pumps in India could theoretically reach 214 million ton if the government would introduce a subsidy system that would allow project developers to close the gap with CER revenues. Under more realistic assumptions about diffusion of SPV technologies based on past experiences with the government-run programmes, annual CER volumes by 2012 could reach 50,000–100,000 and 0.25–0.75 million by 2020. This would still require some government support to close the gap between the mitigation cost of 24 € and the CER price for diesel pumps and a substantial subsidy of about 80% of system cost to cover the difference between 200 € mitigation cost and CER price for the electric pumpsets.

The projections based on the past diffusion trend indicate that in India, even with highly favorable assumptions, the dissemination of SPV pumps for irrigation water pumping is not likely to reach its maximum estimated potential in another 100 years. CDM could help to achieve the maximum utilization potential more rapidly as compared to the current diffusion trend if supportive policies are introduced. However, it is questionable whether such a policy would be an optimal use of scarce resources, given the fact that CDM projects in other sectors are much more attractive.

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