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LETTER

Unleashing the potential of solar irrigation in Bangladesh: key lessons from different implementation models

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Abstract

The transition to solar-powered irrigation in South Asia offers an opportunity to cut greenhouse gas emissions and reduce dependency on expensive diesel. However, appropriate institutional and financial models are required to scale up this technology. Three different solar irrigation pump (SIP) implementation modalities coexist in Bangladesh, providing a good opportunity to evaluate and gain insightful knowledge on the solarization process. These conclusions are also applicable to neighboring countries dealing with comparable problems. The three models are (i) community-managed SIP model, (ii) individual ownership model, and (iii) fee-for-service model. In this article, we argue that the fee-for-service model involving a market-based approach and public-private partnership is the most promising in terms of addressing two main challenges in solarization, i.e. high capex financing requirement and generation of sufficient demand. In terms of achieving equity in SIP access and groundwater sustainability, all three models have their respective pros and cons. However, the financial sustainability of SIPs is under threat due to the significant project costs. It is imperative to expedite the integration of SIPs with the national power grid while implementing supportive government policies. This includes enhancing buy-back tariffs and introducing net-metering options to ensure long-term sustainability.

1. Introduction

Solar irrigation pumps (SIPs) were first developed in the late 1970s (Chandel *et al* 2015), yet it was only in the 2010s that the use of this innovation picked up and its full potential for the energy transition in the agricultural sector became evident. Improved technology and lower costs, particularly in photovoltaic (PV) panels, have been the main drivers of solar irrigation system development (Hartung and Pluschke 2018, Otoo *et al* 2018, Agrawal and Jain 2019, Shirsath *et al* 2020). Since then, and in parallel with the reduction in costs, irrigation using PV-powered systems has gained momentum as a climate-smart technology promoted by development partners and the research community (Lefore *et al* 2021). Solar irrigation has become a part of the climate change agenda, not only for its mitigation potential but also as an adaptation tool in response to climatic uncertainties (IRENA 2016, Caretta *et al* 2022).

Transitioning a significant number of diesel and electric pumps into solar-powered systems in South Asia heralds a double win in alleviating carbon emissions and reducing the financial burden, especially considering the interplay of the energy-groundwater nexus and perverse incentives related to fossil fuel subsidies (Shah *et al* 2018). India has been a leader in this transition, with both off-grid and grid-connected units, yet progress has been slower in other countries in the region, including Bangladesh. As part of its possible mitigation actions, the Government of Bangladesh has set a target of 176 MW of solar irrigation in the unconditional scenario of the nationally determined contributions (NDC) commitments and an additional 164 MW in the conditional scenario (MoEFCC 2021). So far, as of March 2023, 51.3 MW and 2798 units have been installed (SREDA 2023).

Interestingly, despite limited SIPs, Bangladesh has three competing models for solar irrigation: fully subsidized community-managed SIPs; individually owned SIPs, and the fee-for-service-model. The individual ownership model, financed through a combination of subsidies, loans, and equity, is a popular approach for deploying SIPs. India's flagship PM-KUSUM scheme is a prime example. Slight variations exist, where implementing agencies themselves arrange the loan financing for farmers, repaid through monthly/yearly instalments. Examples include FuturePump and SunCulture in Kenya; Sunfarmer in Nepal etc (Holthaus *et al* 2017, Shah *et al* 2018). The other popular model is community-managed SIPs, with full or partial subsidies, mostly through government/donor-funded programs (examples exist in Nepal Terai, and Eastern India, among others) (Agrawal and Jain 2019, Bastakoti *et al* 2020). The third model involves private entities owning the system and then renting out mobile solar pumps/panels or selling water directly as a service to farmers. Examples of renting out can be found in India, with Claro Energy in Bihar, and Mobile Urja in Odisha (Agrawal and Jain 2019). For direct water selling by a private company as a fee-for-service model, there is one pilot in India by Oorja Development Solutions (Howard *et al* 2020), but Bangladesh is unique in deploying at scale the fee-for-service model. We use the opportunity in Bangladesh to study these alternative models being deployed simultaneously in the same region and assess how they can respond to key challenges in scaling up solar irrigation. Our analysis builds on a combination of quantitative and qualitative methods used to collect data on the solar irrigation sector of Bangladesh. For the fee-for-service Infrastructure Development Corporation Limited (IDCOL) SIPs, the analysis is based on telephonic surveys conducted three times a year since 2021 for a representative sample of 83 SIPs and on a household survey of 1200 sample size undertaken in 2021 in villages with existing SIPs, villages identified as potential locations for future SIPs, and control villages without SIPs. We also collected secondary data from IDCOL and conducted key informant interviews (KIIs) with IDCOL officials. For the individual and community-managed models, the analysis is anchored on Focus Group Discussions and KIIs conducted with donors, government officials, and researchers working in the solar irrigation sector of Bangladesh.

This article examines the development of solar irrigation within the context of the water-food-energy nexus in Bangladesh. As a densely populated region with limited land, ensuring food security is the government's top priority. This requires intensified cropping through expanded irrigation. Historically, irrigation expansion has relied on groundwater abstraction using pumps powered by imported diesel. This not only places a significant financial burden on the country but also exposes its food security to international oil price shocks. In 2023, the government announced plans to replace all diesel pumps with SIPs for these reasons. However, since SIPs have no running fuel costs, there's a risk of excessive pumping negatively affecting groundwater sustainability and food security. To address both immediate food security risks from energy sector shocks and longer-term water and food security concerns arising from groundwater over-extraction, an energy transition through an appropriate SIP promotion model is crucial. This issue extends beyond Bangladesh, affecting regions that rely on costly diesel for irrigation, necessitating a transition to solar. From this perspective, we explore various business models, their associated challenges, and potential responses in this article.

2. Energy-irrigation nexus in Bangladesh

Bangladesh's government liberalized imports of irrigation equipment after the 1988 floods and 1990 cyclones, leading to a surge in shallow tubewells (STWs) from China and India (0.16 million in 1986–87 to 1.36 million in 2018–19). In 1985–86, the total irrigated area was 1.7 million hectares, which tripled to 5.6 million hectares in 2018–19, with the proportion of surface-water irrigated area reducing from 48% to 27% in this period. The same period saw STW irrigated area rising from 34% to 54%; while the share of irrigated area under DTW (from 17% to 19%) and low lift pumps (LLPs) (from 20% to 22%) remaining more or less constant. The share of area under traditional and gravity flow methods, however, decreased substantially during this period. Since boro paddy is entirely dependent on irrigation, the groundwater irrigation expansion led to expansion in boro cultivation (Rahman and Rahman 2009, Hossain 2010, Mottaleb *et al* 2019) (figure 1(a)). Most of the growth in food-grains production after 1990 comes from the increase in boro production (figure 1(b)) (Finance Division: MoF 2005, 2020).

But this led to an increased dependency on imported diesel (∼90% diesel in Bangladesh is imported), and it has significant implications for the government's exchequer (BPC 2022, Mitra *et al* 2022b). Imported fuel dependency burdens the country's balance of payments and foreign exchange reserves[5]. It also makes agriculture vulnerable to international fuel price shocks, as seen during the 2022 energy crisis due to the Russia–Ukraine war. Rising international oil prices require that either the government subsidizes domestic diesel use or farmers have to bear the

[5] For the period between 2009 to 10–2019–20, forex spending on petroleum was 7.8% of the total import cost of 40.9 billion USD for Bangladesh (Bangladesh Bank 2023).

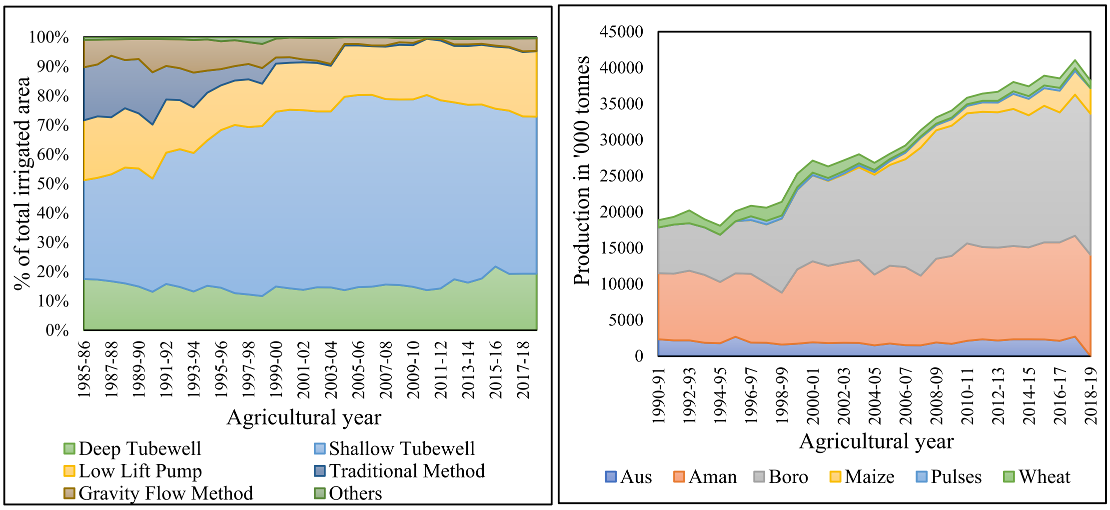

Figure 1. (a) Share of different irrigation methods in Bangladesh from 1986—2019. (b) Production of major food grains in Bangladesh, 1991–2019.
Note: Aman paddy cultivated during monsoon season (June/July–October/November) and is mostly rainfed. Boro paddy is grown between January/February–April/May, completely dependent on irrigation. Aus paddy cultivated between April/May–July/August, requiring supplementary irrigation especially at the beginning.

high cost of diesel (Mitra *et al* 2022b). Diesel dependence is also harmful for the environment. Emissions from agricultural diesel use, most of which are for diesel-based irrigation, is estimated to account for almost 4.4% of total annual production-based CO_2 emissions[6] as estimated in 2017 (Ritchie and Roser 2017). Diesel exhaust also contains harmful nitrogen oxides and particulate matter, known as 'black smoke,' which are dangerous to human health and can cause cancer.(IARC 2012, Frondel and Vance 2014).

Accordingly, the 'Renewable Energy Policy of Bangladesh' 2008 (GoB 2008) set to reduce reliance on imported fossil fuels by 2020, aiming for 10% of power demand from renewable sources like solar, hydropower, wind, biomass, and biogas

3. Landscape of the solar irrigation sector

As of August 2022, only 3.6% of the total installed electricity capacity in Bangladesh was from renewable sources (909.2 megawatts (MW)), out of which solar accounted for 75% of all renewable energy (SREDA 2023). SIPs comprised ∼8% of the total installed solar capacity (SREDA 2023, Mitra *et al* 2022b). Thus Bangladesh's progress towards achieving 10% renewable energy by 2020 has been slower than anticipated (GoB 2008). However, the government has set ambitious targets to increase solar irrigation capacity by 3–6 times in the coming decade, aligning with the government's Nationally Determined Contribution targets of reducing GHG emissions unconditionally by 6.73% below BAU in 2030 and 15.12% in the conditional scenario of external financial and technical support (MoEFCC 2021).

By mid-2022, Bangladesh had 2716 SIPs with a total capacity of 50.4 MW. IDCOL, the dominant player in the sector, financed 1523 SIPs (42.1 MW capacity). Other competing models include the 'grid-integrated individual ownership model' under the Bangladesh Rural Electricity Board (BREB) and the 'community-managed model' under the Barind Multipurpose Development Authority (BMDA) and Bangladesh Agriculture Development Corporation (BADC). Most SIPs are located in the North-west region, including Rangpur and Rajshahi divisions (primarily BMDA and IDCOL pumps are located here), and the South-west region in the Khulna Division (mostly IDCOL pumps). BADC and BREB pumps also exist in other areas, including Mymensingh, Dhaka, and Barisal districts. (figure 2).

These four organizations (IDCOL, BMDA, BADC, and BREB) comprise 97% of the total number of SIPs (2716) and 99% of the total installed SIP capacity (50.4 MW) (figure 3).

3.1. Fee-for-service model

IDCOL's fee-for-service model is a unique public-private partnership in the solar irrigation sector. IDCOL is a government-owned non-banking financial institution (NBFI) that provides loans to private sector investors (called sponsors) for installing SIPs. Sponsors, either private limited companies or NGOs, invest in SIP equipment and then own and operate the system. IDCOL provides grants up to 50% of the total cost, with 35% financed through a loan and the remaining 15% as a down payment. The loan must be repaid at a 6% interest rate within ten

[6] The agricultural sector consumed around 1.09 million metric tonnes of diesel in 2017–18, accounting for ∼3.5 million CO_2 emissions annually.

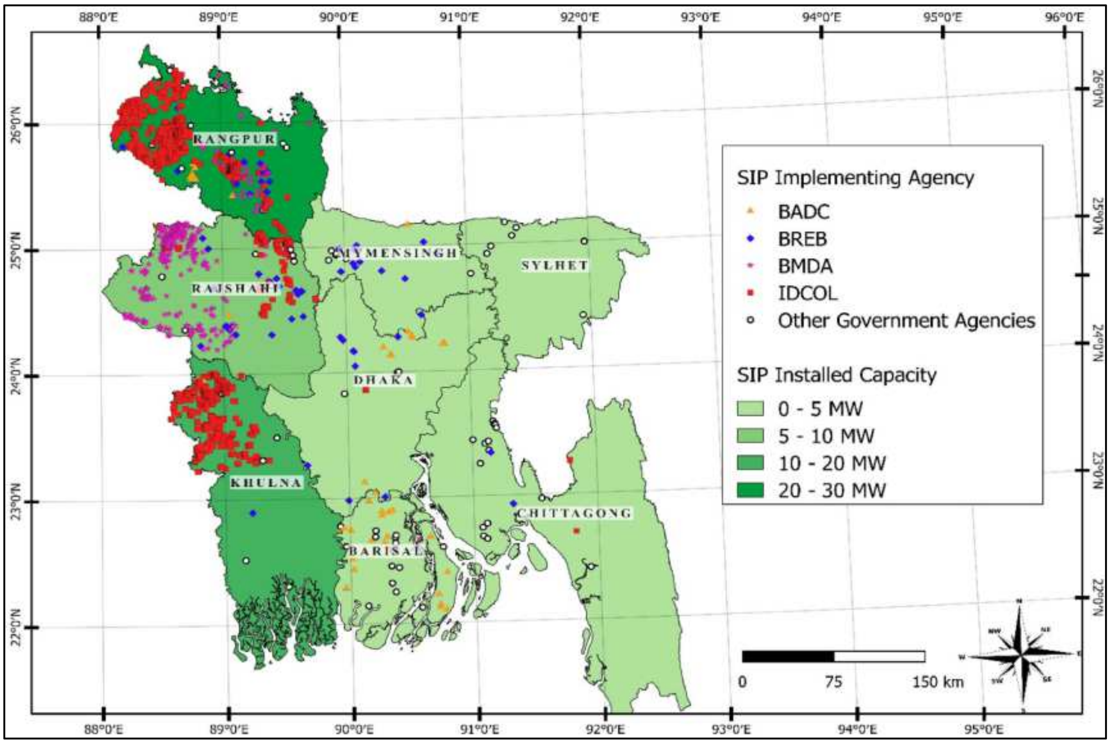

Figure 2. SIP locations in Bangladesh.

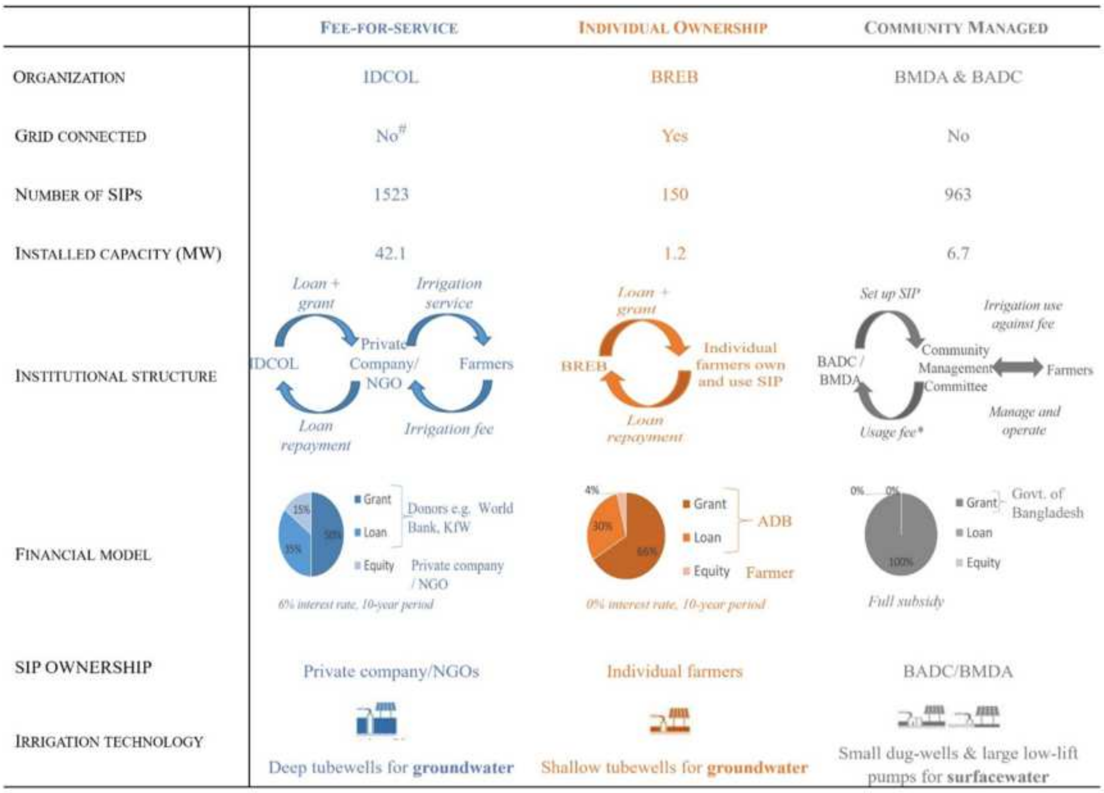

Figure 3. Different Institutional Models of SIP in Bangladesh.
IDCOL is piloting grid connection in 9 SIP units. * BADC has fixed yearly usage fees received from community, and for BMDA the usage fees depend on the number of hours the SIP was used.

years. Sponsors buy equipment from certified suppliers, lease land from local farmers, and set up the SIP system. Sponsors then employ a local community member to operate the pump and supply water to plots, using the revenues from water selling to repay loans and cover operation and maintenance costs. The price at which sponsors sell water is *de facto* regulated by local groundwater markets, including water prices charged by diesel pump owners or electricity-powered irrigation service providers. Upon repayment, the sponsor gains ownership of the SIP system.

3.2. Community-managed SIP model

The second SIP model in Bangladesh provides 100% grant financing on the capital expenditure for installation. Government institutions like BMDA and BADC follow this model, focusing on smaller SIPs (4–5 hp) installed on dug wells and larger solar LLPs that pump from rivers and canals. From their initial mandates, BADC is responsible for sustainable management of agricultural input supply and providing irrigation facilities to farmers across Bangladesh, while BMDA is specifically responsible for the development of the Barind Tract area in North-West Bangladesh.

To set up the SIP, the department (BMDA/BADC) contracts a farmer to use their land for a certain number of years. Once the pump is set up, the operation and maintenance of the SIP infrastructure are handed over to the community through a farmers' committee. The farmer whose land hosts the pump mostly serves as the operator, and the farmers' group determines irrigation fees to cover operation and maintenance expenses. Technical and financial support for maintenance remains covered by the supporting government department, and they collect participation fees from the farmers' group. For BADC, there is an initial participation fee for the farmers' group (240 USD[7] for 7.5 hp; 370 USD for >10 hp) and then a fixed yearly payment between 50–100 USD (depending on the pump size). For BMDA dug wells, there are currently no fees, but for solar LLPs, there is a prepaid meter system where farmers are charged between $1.2-1.9$ USD/h^{-1}.

3.3. Individual ownership model

BREB's individual ownership model allows individual farmers to apply for a SIP system to be installed on their land. BREB is responsible for rural electrification under the Ministry of Power, Energy, and Mineral Resources. Farmers receive a 65% grant for the total cost, with the remaining amount split between a 30% loan and a 5% upfront payment. The loan repayment time is ten years. The systems are typically smaller and operated by individual farmers, who operate and maintain them independently. BREB's individual ownership model connects SIPs to the grid, allowing owners to sell excess power at a designated tariff.

4. Mitigation and adaptation co-benefits of solar irrigation

The primary stated objective of promoting solar irrigation in Bangladesh is to reduce dependency on imported diesel and its subsidy burden. Yet beyond this primary objective, SIPs can also have significant adaptation co-benefits for the farmers.

4.1. Mitigation benefit

We find that diesel use within the SIP command area is minimal, with only 3% of the areas irrigated from diesel pumps during *kharif* 1 (*boro* season), 8% during *kharif* 2 (*aman* season), and 22% during the *rabi* season. The slightly higher use of diesel during the *rabi* season is associated with vegetable cultivation, which requires controlled water application that cannot always be delivered by high-discharge larger SIPs.

To estimate diesel use per unit of land, we collected data from the household survey on the average number of irrigation hours and the average hourly diesel consumption for typical diesel pumps. Using this information, we calculate the reduction in diesel use and CO_2 emissions from SIP use[8]. On average, irrigating an acre of land with diesel pumps for three seasons in a year requires 65 l of diesel, but within the SIP command area, this reduces to just seven litres of diesel per acre. Thus shifting to solar potentially saves 58 l/acres of diesel on average, which translates into avoiding 2.8 metric tonnes of CO_2 emissions per SIP (US EPA 2015)[9]. By considering the average command area of a typical diesel pump (5.9 acres) and IDCOL SIP (18 acres) respectively, we calculate that replacing all 1.24 million diesel pumps will require the installation of ~400 000 IDCOL-type SIPs. This can potentially reduce 1.2 million metric tonnes of CO_2 emissions per year (Mitra *et al* 2022a). However such large-scale transition from diesel to solar entails substantial economic costs that are not discussed here. Also we have not done a life-cycle comparison of diesel vis-a-vis solar and there can be secondary environmental pollutions from the disposal of the

[7] 1 USD = 94.68 BDT as per Bangladesh Bank's exchange rate of Taka for 26 July 2022.

[8] These calculations ignore a potential displacement of diesel pumps from the SIP command area to newly irrigated and cultivated area. Access to cheaper irrigation through solar in one plot is unlikely to change the return from diesel irrigation in another plot in most cases and hence displacement of diesel use in previously unirrigated areas is unlikely. In our sample, even considering outside the SIP command area, only 14% of the total cultivated area was diesel-irrigated. But still, depending on which areas SIPs are targeted, the calculations on actual mitigation might differ.

[9] We use the conversion factor for CO_2 emissions from diesel using EPA (2015) as 10180 grams/gallon = 0.0026893 metric tonnes/litre. Since the average SIP command area is 18 acres and for each acre of SIP command area, diesel use is reduced by 58 l, hence each SIP reduces 1044 l of diesel i.e. 1044*0.0026893 metric tonnes = 2.8 metric tonnes of CO_2 reduction per SIP.

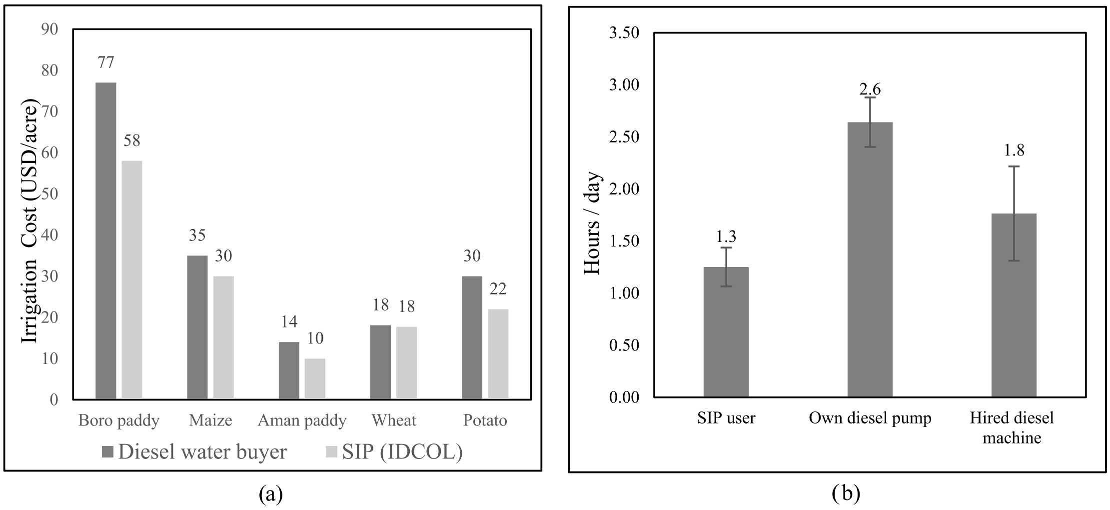

Figure 4. (a) Irrigation cost comparison across diesel and IDCOLSIPs. (b) Average hours spent on irrigation on a typical day during the *boro* season.

replaced diesel pumps and e-waste resulting from the solar panels. All these need to be carefully considered before deciding on any large-scale transition.

4.2. Adaptation co-benefits

The first adaptation co-benefit of SIPs is the reduced costs of irrigation for users. Buying water from SIPs is significantly cheaper by 20%–30% than buying from diesel pumps for irrigating *boro*, *aman*, and potatoes. For maize and wheat the difference is not significant (figure 4(a)) (Buisson *et al* 2022). Reduced irrigation costs also enable more farmers to provide supplementary irrigation in case of delayed monsoon during *kharif* 2 season, instead of waiting for rainfall and thus protecting their yield (Buisson *et al* 2022).

The second co-benefit is savings in time and labor costs. The cost of using a diesel pump for irrigating plots in Bangladesh is high, as it involves purchasing diesel, transporting and installing the pump, monitoring irrigation delivery, and turning off the pump when enough water is delivered. This can result in expenses such as wages paid to hired labor or the opportunity cost of lost wages. In contrast, the fee-for-service model involves a paid pump-operator operating the pump and ensuring adequate water supply. Water buyers from IDCOL SIPs save on average 23.4 h in the dry season compared to those who use their own diesel pumps and 9 h when compared with those buying water from diesel pumps (figure 4(b)). In monetary terms, this translates into a saving between 5–12 USD in terms of lost wages[10] (Buisson *et al* 2022).

[10] The median daily wage rate for men in our sample villages was 4–5 USD/d^{-1}.

5. Evaluation of alternative SIP models

The three SIP models in Bangladesh are assessed in the following sub-sections with respect to equity in access to irrigation, groundwater sustainability, ease of investment, generating demand, and financial sustainability. This assessment is synthesized in figure 5 and highlights the potential of each model in tackling the challenges of scaling up SIPs.

5.1. Equity in access

Cheaper irrigation in off-grid areas should benefit marginalized farmers, but the high capital costs of SIPs create a risk that influential farmers may receive more benefits. Even with subsidy, without pro-active targeting of marginalized farmers, there is risk of elite capture. This is often the case for government-subsidized community-managed models of BMDA and BADC without an explicit policy of targeting marginalized groups. Under this model, local elites on whose land the pumps are mostly set up become the de-facto water-sellers and retain substantial control over the irrigation service and tariffs. Many community-managed SIPs lack a functional managing committee.

In the fee-for-service model, the CAPEX subsidy is given to sponsors, not directly to farmers. This commercial model aims to maximize profit by prioritizing command area expansion, servicing more farmers, and reducing the arbitrary power of operators or individual pump owners. In the individual model of BREB, there is still a considerable upfront cost, which may be beyond the reach of poorer farmers.

Equity is access also implies that the irrigation rates charged from water buyers are not exorbitantly

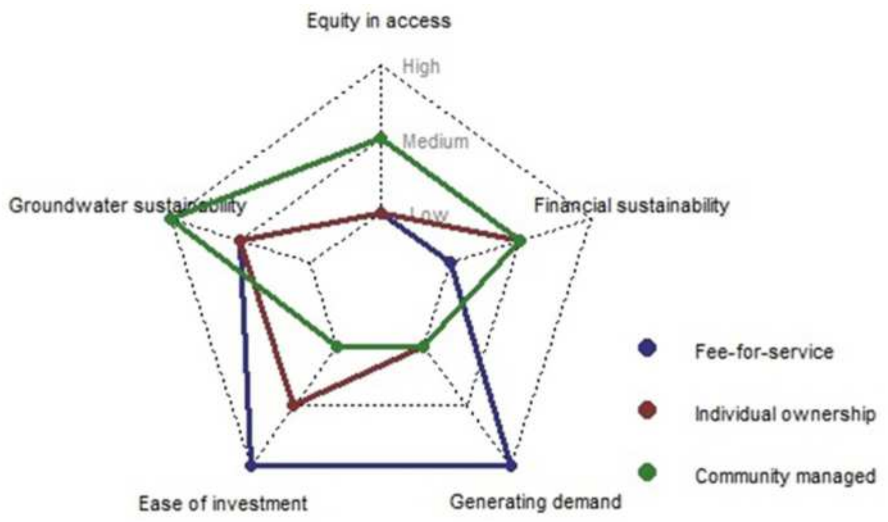

Figure 5. Qualitative rating by authors for SIP models in Bangladesh to tackle challenges of scaling up SIPs.

high and hence it is important for the implementing agencies, to monitor the irrigation rates charged from water buyers. This is particularly important due to the tubewell permit system established under the new 'Groundwater Management in Agricultural Activities Act,' which can restrict new electric connections within the command area of existing SIPs. If irrigation rates charged by sponsors are not monitored after loan repayment, it could lead to local monopolies of for-profit sponsors charging higher rates compared to electric pumps while denying access to new connections within the command area. This risk of local monopolies is lower in fully subsidized community-managed systems, as ownership and monitoring of the pumps remain with BADC and BMDA throughout the duration.

Community-managed systems have a freer hand in targeting marginalized farmers, and the benefits can go directly to farmers; but they are also prone to the risk of elite capture and non-functioning management committees. Given these trade-offs, we rate community-managed systems as medium on equity. Individual ownership model excludes poorer farmers without proper targeting through a preferential mechanism. While fee-for-service model runs the risk of creating local monopolies by private companies in longer run without proper monitoring (which is costly). Also market-based model with lower subsidy implies monetary benefits to farmers being lower. Accordingly we categorize individual ownership and fee-for-service models as having low equity in access.

5.2. Groundwater sustainability

Introducing SIPs instead of diesel pumps translates into a near-zero marginal cost of irrigation, which in increasing irrigation intensity and promoting water-intensive crops may sharpen the risk of over-extraction of groundwater. However, in Bangladesh, the institutional and financial models minimize the risk of groundwater over-utilization. For the fee-for-service model, the sponsor's objective is to maximize profit, and he is thus incentivized to expand the command area and providing more water than required would reduce the potential command area that can be served. Still, in this model, there might be an incentive to shift farmers towards *boro* cultivation, to earn higher revenue. But sponsors also need to target areas that were already growing *boro* pre-SIP installation for financial sustainability. Hence the scope for further crop change, and an impact on groundwater use is limited.

For BMDA and BADC, SIPs are either low-lift pumps irrigating from surface water sources or dug wells targeted for vegetable cultivation with relatively low water requirements. So, by design, the possibility of groundwater over-extraction is ruled out.

Finally, individual BREB pumps are all grid-connected. As a result, there is an opportunity cost of using solar energy for pumping rather than selling it back to the grid. Also, all the SIP systems in Bangladesh have underground pipe systems for delivery, ensuring increased water use efficiency as compared to diesel-operated systems, which usually use open furrow or flexible plastic pipes.

Community-managed models in Bangladesh are exclusively surface-water system, earning a high groundwater sustainability rating, while the other two models receive a medium rating because although they use groundwater, but they have inherent incentives to reduce wastage in use (selling excess energy to the grid for the individual model and expanding the command area for the fee-for-service model).

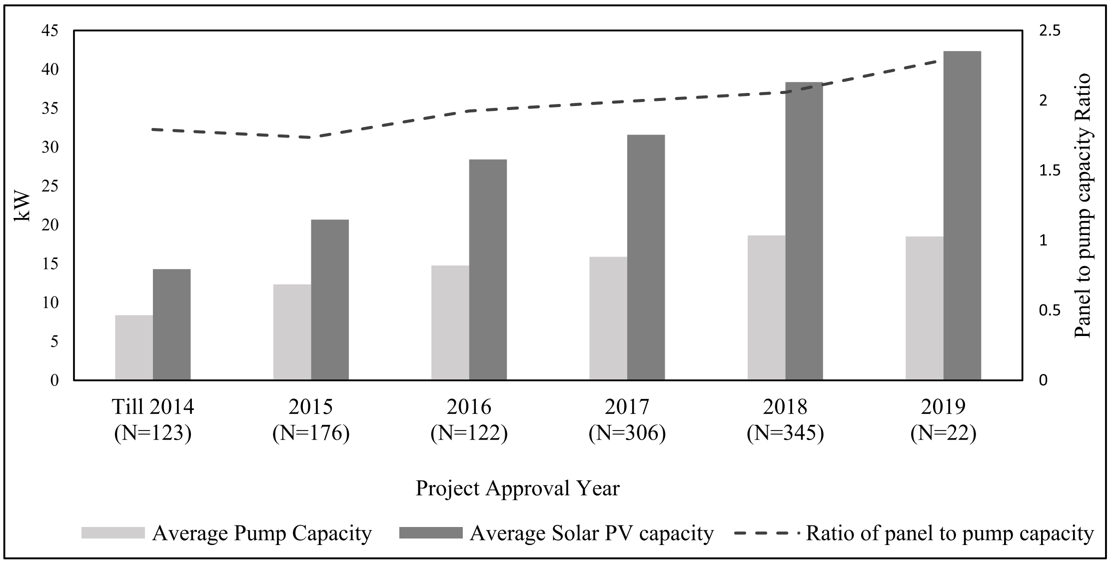

Figure 6. Average pump and panel capacity in IDCOL locations over time.

5.3. Ease of investment including CAPEX availability

Solar pumps are characterized by higher initial investments, but lower operational costs as compared to diesel pumps. The cost of an IDCOL SIP is around 2500 USD per hp, while BREB-installed pumps have project costs ranging from 2500–3500 USD per hp. These costs are substantially higher than those observed in India[11] but relatively similar to other countries in the region such as Nepal[12]. One of the reasons for high prices in Bangladesh is due to over-sizing, with panel-pump capacity ratio ranging between 1.8–1.9 times (figure 6). Oversizing is due to foggy weather conditions in late January/early February, which coincides with peak irrigation demand for *boro* paddy. Also, all SIPs in Bangladesh are equipped with underground pipes for water conveyance, which can cost up to 27% of the system's cost.

Given these high costs, scaling up of SIPs faces challenges due to liquidity constraints and risk aversion from farmers and investors. High grant financing is necessary to overcome these barriers. BMDA and BADC community-managed models offer 100% CAPEX subsidies. The subsidy for BREB model ranges from 62%–66%, along with ~4% as upfront equity by the farmer and the rest as 0% interest loan. Despite the subsidy, the upfront equity still acts as a barrier and the demand for SIPs under BREB remains low, with only 150 pumps installed out of a target of 2000 by June 2022.

IDCOL's fee-for-service model enables smallholder farmers to access solar irrigation services with comparatively lower subsidies (50% subsidy). An intermediator, like a private company or NGO, takes on the risk of setting up the irrigation service business thus transferring the investment risk from farmers.

Because of this less reliance on subsidies and shift in investment risks to private companies, we rate the fee-for-service model as high in terms of ease of investment. The community-managed model in Bangladesh receives a medium rating since it avoids farmers' liquidity constraints and risk aversion but depends fully on subsidies. The individual ownership model is rated low for ease of investment as it requires high subsidies and does not fully alleviate farmers' liquidity constraints and risk aversion issues.

5.4. Generating demand for SIPs

Generating demand for SIPs involves substantial transaction costs, such as providing information and knowledge to farmers and convincing them of the benefits of SIPs. Additionally, since 2018, farmers have to obtain tubewell permits from the local *Upazilla* irrigation committee, which adds transactional costs for smallholder farmers with thinner social capital and networks (Mukherji *et al* 2012).

Government officials generate demand for SIPs for projects under BMDA, BADC, and BREB, which limits the model's scalability, as evidenced by the relatively slower progress of their SIP programs. Under fee-for-service model, sponsors identify potential locations for setting up SIPs based on local agro-environmental conditions, including groundwater availability, cropping patterns, and existing irrigation

[11] In India, SIP cost is between 500–750 USD/hp for 10 hp pumps, and even for 1 hp pumps, the cost is still in the range of 1000–2500 USD/hp (MNRE 2019).

[12] However, the off-grid solar pumps in Nepal are also quite costly 2500–4000 USD per hp, since most of the SIP systems in Nepal are very small at 1 hp or 2 hp (Kafle *et al* 2022), which contributes to relatively higher prices.

infrastructures. Sponsors are responsible for convincing farmers within the SIP command area to shift from diesel, with sponsors having an incentive to incur these costs to generate demand for SIPs. The public-private partnership under the fee-for-service model enables private organizations to internalize these transaction costs in their net return calculations and reduce transaction costs by operating at scale.

The fee-for-service model's feature of working at scale and internalizing transaction costs gives it a high rating for generating SIP demand, while both community managed and individual ownership models are rated low due to high transaction costs associated with involving smallholder farmers in SIP ownership and management, which are not internalized in the current model and hinder their progress.

5.5. Financial sustainability

SIPs can be a financially sustainable alternative to diesel-based irrigation if the total private and social benefits from replacing diesel are greater than the cost (Closas and Rap 2017). The average project cost of IDCOL SIPs is around 48 000 USD, and assuming a 20 yr lifespan at a 6% interest rate, this implies at least 3900 USD worth of social and personal benefits per year should accrue for 20 yr to break even the investment cost of 48 000 USD[13]. On average, 2.8 metric tonnes of CO_2 per SIP are mitigated, which translates into a social benefit of 518 USD/year[14]. Assuming other social externalities to be minimal (for example, any environmental impact in terms of changes in groundwater use or cropping pattern change), the private yearly benefit from using solar should be around 3400 USD/year to break even. The average command area for IDCOL SIPs is 18 acres, which implies that the yearly benefit per acre should be at least ~190 USD[15].

Hence, SIPs are justified only when farmers cultivate water-intensive crops like boro, which currently accounts for 65%–70% of the total revenue of IDCOL SIPs (Mitra *et al* 2021), but even then, the net benefit from reducing the energy cost of irrigating *boro* is unlikely to yield sufficiently high benefits. This is because, in Bangladesh, similar to eastern IGP, there is a relatively shallow groundwater level and abundant monsoon season that implies demand for irrigation is limited to only 4–5 months per year during the dry season (Buisson *et al* 2022). Hence, even with *boro* cultivation, the capacity utilization of solar panels remains limited. So, for financial sustainability, the cost of these systems needs to be reduced over time (through a reduction in import duties amongst others), and till then, support from subsidies is crucial.

But also, the capacity utilization of these systems needs to be increased through alternative uses of energy. For that, grid integration of SIPs needs to be promoted wherever feasible (other options, like using excess solar energy for running agri-machinery for threshing or husking, have limited scope[16]). Grid connection can make SIPs financially viable by increasing capacity utilization and contributing to the country's goal of a 10% renewable energy mix by connecting solar infrastructure to the national grid with limited investments.

However, institutional interventions are also needed to improve the economics of grid-integrated systems. Recovering the additional investment of grid integration can take up to 10–12 yr (Mitra and Mukherji 2022) at current buyback rate of 4.6 cents/unit rate. This rate is the subsidized rate BREB pays to the Bangladesh Power Development Board (BPDB) for electricity. However, the average generation cost for BPDB is higher at 7 cents/unit (in 2020–21) and can be as high as 8.5 cents/unit when bought from private companies (in 2020–21). The subsidy given to fossil fuel energy sources can be similarly provided to BREB for purchasing clean energy from grid-integrated SIPs, allowing for a substantially higher tariff to be paid to SIP owners. Another option is to allow net metering since having electricity as a supplementary energy source during periods of high irrigation demand or low power generation can help bring a larger command area per SIP. However, to prevent SIP owners from relying solely on the grid and abandoning their solar systems, policy experiments such as capping energy evacuation or allowing only net exporters to remain grid-connected may need to be piloted.

The fee-for-service model rates low in financial sustainability for the investors due to low capacity utilization, high costs, and low subsidy dependency. In individual ownership model, being grid integrated with higher subsidy and zero-percent interest, recovering investment costs are higher making its rating as medium. For community managed models, full subsidy means no risk for farmers to recover costs, but

[13] In this calculation, we estimate what should be the constant yearly benefit flow (R) from SIP over its lifespan of 20 yr, so that the Net present value (NPV) i.e. $= \sum_{t=0}^{19} \frac{R}{(1+i)^t}$ at least break-even the initial investment cost of 48 000 USD. Here i is the discount rate = interest rate of 6%. Solving this equation gives the minimum yearly benefit for break-even, i.e. R = 3950 USD = ~3900 USD. In this calculation, we are ignoring yearly operational costs, maintenance costs, and depreciation (which should be included if we expect the sponsor to reinvest in solar after 20 yr). Considering these costs would imply even higher yearly benefits to break even.

[14] We are using a recent estimate of the mean social cost of carbon at 185 USD/tonne from Rennert *et al* (2022); but they also provide the 5%–95% range of the social cost of carbon to be between 44–413 USD/tonne. This huge variation in the social cost of carbon estimate substantially affects these financial sustainability calculations.

[15] For comparison, the cost of irrigation for *boro*, the most water-guzzling crop for a diesel water buyer, is between 74–84 USD/acre on average.

[16] SIPs are mostly located in the middle of farmers' fields, making it difficult for them to bring their produce for husking, threshing, or grinding to the SIP's location (Mitra and Mukherji 2022).

low-capacity utilization both due to being off-grid and targeted in regions with less irrigation use, leads us to rate this model as medium on this parameter.

6. Conclusion

Solar energy for irrigation is a promising option for diesel-irrigated off-grid areas in Bangladesh, as it reduces greenhouse gas emissions and helps achieve energy security by reducing dependence on expensive diesel. However, high initial costs pose challenges to scaling up this technology, particularly in rural areas with marginal and small farmers. The situation in Bangladesh is unique due to the coexistence of three distinct institutional models for SIPs even at a nascent stage. Each of these models has its own set of advantages and disadvantages, and their suitability varies across different regions based on factors such as cropping patterns, irrigation sources, groundwater availability, distance to the grid, and more. Considering the complexity of Bangladesh's agricultural system, characterized by small landholdings and tenant farmers, a diverse range of institutional models is necessary for effective scaling of SIPs.

However, there are three key areas where policy interventions are needed. First, SIP project costs are very high in Bangladesh. Collaborative efforts with manufacturers and importers to lower SIP prices, particularly by enhancing panel supply chains, are essential. Secondly, it is vital to speed up the grid integration process by providing the right incentives (better buy-back price or allowing net metering), as it would popularize this technology by making it financially sustainable. Lastly, the government should incorporate regulations for handling PV module waste, aligning with its e-waste management rules. Effective PV waste management mitigates environmental risks and offers economic benefits through resource reclamation from modules.

The experience of Bangladesh with SIPs replacing diesel can provide valuable lessons for neighbouring Indian states, which face similar energy-irrigation nexuses and depend on expensive diesel for irrigation. Sharing these lessons and trying out different models for scaling up solar pumps would be valuable for replacing fossil fuel irrigation in the region.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Ethical Statements

This research was reviewed by the IWMI Institutional Review Board (IRB) and received an exempt certification (# #2020_25a) in November 2020. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Agrawal S and Jain A 2019 Sustainable deployment of solar irrigation pumps: key determinants and strategies *WIREs Energy Environ.* **8** e325

Bangladesh Bank 2023 *Bangladesh Import Payments: Category-Wise Imports* (available at: www.bb.org.bd/en/index.php/econdata/imprtindex)

Bastakoti R, Raut M and Thapa B R 2020 *Groundwater Governance and Adoption of Solar-Powered Irrigation Pumps: Experiences from the Eastern Gangetic Plains* (International Water Management Institute) (https://doi.org/10.1596/33245)

BPC 2022 Sectorwise sale of petroleum (available at: www.bpc.gov.bd/site/page/d6742c5d-2775-4014-b5f7-ad1cc5b1e6f5/-)

Buisson M-C, Mitra A, Osmani Z, Habib A and Mukherji A 2022 *Impact Assessment of Solar Irrigation Pumps (SIP) in Bangladesh: Baseline Technical Report* (International Water Management Institute) (https://doi.org/10.5337/2022.230)
Caretta M A *et al* 2022 Water *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H-O Pörtner *et al* (Cambridge University Press) (https://doi.org/10.1017/9781009325844.006)
Chandel S S, Nagaraju Naik M and Chandel R 2015 Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies *Renew. Sustain. Energy Rev.* **49** 1084–99
Closas A and Rap E 2017 Solar-based groundwater pumping for irrigation: sustainability, policies, and limitations *Energy Policy* **104** 33–37
Finance Division: MoF 2005 Bangladesh economic review
Finance Division: MoF 2020 Bangladesh economic review
Frondel M and Vance C 2014 More pain at the diesel pump?: an econometric comparison of diesel and petrol price elasticities *J. Transp. Econ. Policy* **48** 449–63 (available at: www.jstor.org/stable/24396297)
GoB 2008 *Renewable Energy Policy of Bangladesh* (Power Division, Ministry of Power, Energy And Mineral Resources, Government Of The People's Republic Of Bangladesh)
Hartung H and Pluschke L 2018 The benefits and risks of solar powered irrigation—A global overview (p. 87) (Food and Agriculture Organization of the United Nations (FAO); Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)) (available at: www.fao.org/publications/card/en/c/I9047EN/)
Holthaus J, Pandey B, Foster R, Ngetich B, Mbwika J, Sokolova E and Siminyu P 2017 Accelerating solar water pump sales in kenya: return on investment case studies *Solar World Congress* (International Solar Energy Society, Abu Dhabi) (https://doi.org/10.18086/swc.2017.30.03)
Hossain M 2010 Shallow tubewells, boro rice, and their impact on food security in Bangladesh *Proven Successes in Agricultural Development, A Technical Compendium to Millions Fed* ed D Spielman and R Pandya-Lorch (International Food Policy Research Institute) pp 243–69
Howard J, Wilson F and Aliouche E H 2020 Providing clean energy solutions to India's bottom of the pyramid population (https://doi.org/10.34051/p/2021.13)
IARC 2012 *Diesel Engine Exhaust Carcinogenic* (International Agency for Research on Cancer, World Health Organization)
IRENA 2016 Solar pumping for irrigation improving livelihoods and sustainability (The International Renewable Energy Agency) (available at: www.irena.org/publications/2016/Jun/Solar-Pumping-for-Irrigation-Improving-livelihoods-and-sustainability)
Kafle K, Uprety L, Shrestha G, Pandey V and Mukherji A 2022 Are climate finance subsidies equitably distributed among farmers? Assessing socio-demographics of solar irrigation in Nepal *Energy Res. Soc. Sci.* **91** 102756
Lefore N, Closas A and Schmitter P 2021 Solar for all: a framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture *Energy Policy* **154** 112313
Mitra A, Alam M F and Yashodha Y 2021 Solar irrigation in Bangladesh: a situation analysis report *Technical Report (non-peer reviewed)* (International Water Management Institute (IWMI)) (https://doi.org/10.5337/2021.216)
Mitra A, Buisson M-C, Osmani Z, Habib A, Hossain M, Siddiqui M B and Mukherji A 2022a Mitigation and beyond: multiple co-benefits of solar irrigation in Bangladesh (available at: https://cgspace.cgiar.org/handle/10568/125987)
Mitra A and Mukherji A 2022 Making renewable energy investments sustainable through grid-connected solar pumps in Bangladesh (available at: https://cgspace.cgiar.org/handle/10568/125988)
Mitra A, Yashodha Y, Hossain M, Siddiqui M B and Mukherji A 2022b Institutional modalities for decarbonizing irrigation in Bangladesh (available at: https://cgspace.cgiar.org/handle/10568/125986)
MNRE 2019 Prices discovered and vendors selected through EESL tender under component B of PM-KUSUM scheme (Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan, Ministry of New and Renewable Energy) (available at: https://mnre.gov.in/img/documents/uploads/file_s-1584619769470.pdf)
MoEFCC 2021 Nationally determined contributions (NDCs) 2021, Bangladesh (updated) (Ministry of Environment, Forestry and Climate Change, Government of Bangladesh) (available at: https://unfccc.int/sites/default/files/NDC/2022-06/NDC_submission_20210826revised.pdf)
Mottaleb K A, Krupnik T J, Keil A and Erenstein O 2019 Understanding clients, providers and the institutional dimensions of irrigation services in developing countries: a study of water markets in Bangladesh *Agric. Water Manage.* **222** 242–53
Mukherji A, Shah T and Banerjee P S 2012 *Kick-Starting a Second Green Revolution in Bengal* (Economic and Political Weekly) pp 27–30
Otoo M, Lefore N, Schmitter P, Barron J and Gebregziabher G 2018 Business model scenarios and suitability: smallholder solar pump-based irrigation in Ethiopia. Agricultural water management—making a business case for smallholders *No. 172; IWMI Research Report* (International Water Management Institute (IWMI) p 67 (available at: https://ideas.repec.org//p/ags/iwmirp/273354.html) (https://doi.org/10.2166/wst.2017.600)
Rahman M W and Rahman L P 2009 Impact of irrigation on food security in Bangladesh for the past three decades *J. Environ. Prot.* **1** 40–49
Rennert K *et al* 2022 Comprehensive evidence implies a higher social cost of CO_2 *Nature* **610** 7933
Ritchie H and Roser M 2017 CO_2 and greenhouse gas emissions (OurWorldInData.Org) (available at: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions)
Shah T, Rajan A, Rai G P, Verma S and Durga N 2018 Solar pumps and South Asia's energy-groundwater nexus: exploring implications and reimagining its future *Environ. Res. Lett.* **13** 115003
Shirsath P B, Saini S, Durga N, Senoner D, Ghose N, Verma S and Sikka A 2020 Compendium on solar powered irrigation systems in India (CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)) (available at: www.cgiar.org) (https://doi.org/10.1016/j.worlddev.2020.105064)
SREDA 2023 National database of renewable energy (available at: www.renewableenergy.gov.bd/)
US EPA, O 2015 Greenhouse gases equivalencies calculator—calculations and references (available at: www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references)