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Agricultural Water Management – Making a Business Case for Smallholders

Research Report

Solar Photovoltaic Technology for Small-scale Irrigation in Ghana: Suitability Mapping and Business Models

Solomie Gebrezgabher, Mansoor Leh, Douglas J. Merrey, Theophilus T. Kodua and Petra Schmitter

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International Water Management Institute (IWMI)
P. O. Box 2075, Colombo, Sri Lanka

The authors: Solomie Gebrezgabher is a Researcher – Economics at the International Water Management Institute (IWMI), Accra, Ghana; Mansoor Leh is a Researcher – Spatial Hydrology at IWMI, Colombo, Sri Lanka; Douglas J. Merrey is an independent consultant, Natural Resources Policy and Institutions Specialist, residing in Florida, USA; Theophilus T. Kodua is a PhD student in Agricultural Economics and Policy at the College of Basic and Applied Sciences, University of Ghana, Accra, Ghana; and Petra Schmitter is Research Group Leader – Sustainable and Resilient Food Production Systems at IWMI, Yangon, Myanmar.

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Contents

Acronyms and Abbreviations

AGSI	Association of Ghana Solar Industries
AHP	Analytic Hierarchy Process
BCR	Benefit-cost ratio
BGS	British Geological Survey
BPA	Bui Power Authority
CCI	Climate Change Initiative
CEED	Centre for Empowerment and Enterprise Development
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
ECG	Electricity Company of Ghana
EnDev	Energising Development program
EPA	Environmental Protection Agency
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
FASDEP II	Food and Agriculture Sector Development Policy II
FinGAP	Financing Ghanaian Agricultural Project
GDP	Gross domestic product
GHG	Greenhouse gas
GHS	Ghanaian Cedi
GIDA	Ghana Irrigation Development Authority
GIPC	Ghana Investment Promotion Centre
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GRIDCO	Ghana Grid Company
GSGDA II	Ghana Shared Growth and Development Agenda II
HPW	Hans Peter Werder AG (Swiss company)
IFAD	International Fund for Agricultural Development
IRENA	International Renewable Energy Agency
IRR	Internal rate of return
IUCN	International Union for Conservation of Nature
IWAD	Integrated Water & Agricultural Development Ghana Limited
KITE	Kumasi Institute of Technology, Energy and Environment
KNUST	Kwame Nkrumah University of Science and Technology
KWp	Kilowatt peak
l/s	Liters per second
Mha	Million hectares
MUS	Multiple use water services
MWp	Megawatt peak
NDP	National distribution partner
NEDCo	Northern Electricity Distribution Company
NGO	Nongovernmental organization
NPV	Net present value
NRGP	Northern Rural Growth Programme
O&M	Operation and maintenance
PICA	Power Innovation in Commercial Agriculture (project)
PURC	Public Utilities Regulatory Commission
PV	Photovoltaic
REAG	Renewable Energy Association of Ghana
SEforALL	Sustainable Energy for All
SREP	Scaling-up Renewable Energy Plan
SRTM	Shuttle Radar Topography Mission
SSP	Sales and service partners
UENR	University of Energy and Natural Resources
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
USD	United States Dollar
VRA	Volta River Authority
WHO	World Health Organization

Summary

Access to energy to lift water is a major constraint for smallholder irrigated agriculture in Ghana. Despite high potential and government policy incentives, farmer-led irrigation is still constrained. There are several constraining factors. However, access to water-pumping technologies due to their high upfront costs and high fuel and maintenance costs is the major impediment. In that context, solar photovoltaic (PV) irrigation pumps offer an economically and environmentally sustainable alternative to fossil fuel pumps. This study assesses the feasibility of harnessing solar power for irrigation in smallholder agriculture in Ghana, using elements of business planning and business models with a suitability mapping approach. These approaches take into account the economic as well as environmental sustainability of expanding such technology. Using data from existing solar PV irrigation systems, reports and interviews with key industry actors, this report discusses the regulatory and institutional context for investment in solar PV technology, and outlines the technology supply chain, mapping the key actors and their roles. The financial viability of two empirical business cases – directly funding an agribusiness and subsidizing a cooperative model – is analyzed to assess the feasibility of expanding access to the technology. Business models can play an important role as a decision-making tool to identify conditions that can enable solar PV systems to sustainably enhance farmers' productivity and economic resilience. Three solar PV irrigation business model scenarios are presented based on insights gained from the two empirical cases as well as from analyzing the existing policy and regulatory framework, the technology supply chain and environmental suitability. Our overall conclusion is that the potential for solar PV irrigation pumps is substantial, especially in northern Ghana, although care must be taken to avoid overpumping some aquifers. Achieving this potential will require strengthening the policy framework and making finance available at a reasonable cost. This report identifies several alternative financing mechanisms and business models (for example, multiple use water services) that have been tried elsewhere and may be useful in Ghana, and makes recommendations to enhance the sustainable uptake of solar PV irrigation.

Solar Photovoltaic Technology for Small-scale Irrigation in Ghana: Suitability Mapping and Business Models

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Introduction

The growth rate of agriculture has been declining in Ghana since the 1990s. Agriculture currently employs over 30% of the labor force,[1] but contributes less than 20% to the country's gross domestic product (GDP) (UNECA 2016; GSS 2019). Smallholder farmers, i.e., those cultivating less than two hectares (ha), make up much of this sector: 90% of farm holdings fall within this category (Namara et al. 2010). Supplemental and dry-season irrigation offer a means to make agricultural production more reliable and productive. Yet, according to the Ministry of Food and Agriculture (MoFA 2016), only 3.4% of the total cultivable area is irrigated, covering 9,000 hectares, in the 22 irrigation schemes managed by the Ghana Irrigation Development Authority (GIDA). A second form of irrigation development, not reflected in the official data, is often called 'farmer-led irrigation'. This is characterized by dispersed, household-level technologies, usually owned and managed by individual farmers or small farmer groups (Woodhouse et al. 2016). The area under farmer-led irrigation continues to increase in Ghana. In 2009, there were nearly 170,000 petrol and diesel pumps and 5,000 electric pumps in use, irrigating an estimated 185,000 ha (de Fraiture and Giordano 2014). This is likely to have increased substantially since then.

Given the decline in total rainfall and increasing intermittent dry spells during the rainy season (MoFA 2014), the Ministry of Food and Agriculture is promoting small-scale irrigation as a climate adaptation measure. Further, with incomes rising and dietary patterns changing among middle-income consumers in towns and cities, production of high-value irrigated crops such as vegetables and fruits offers an attractive market opportunity for small-scale farmers. However, access to water for irrigation, energy for pumping, and appropriate irrigation technologies are key requirements to meet this growing market demand.

Various estimates place the irrigation potential of Ghana as being between 0.36 million hectares (Mha) and 1.9 Mha, depending on water access, availability and management (Frenken 2005; Namara et al. 2011; Mendes et al. 2014). Specifically, there is high potential to use shallow groundwater for irrigation to meet smallholder demand (Barry et al. 2010; Drechsel and Keraita 2014; Namara et al. 2014). However, access to energy to lift water is a key constraint, especially for small farmers. Most small-scale irrigators use buckets and watering cans. The majority do not have access to, or a consistent supply of, electricity. Ghana's grid network, covering less than 50% of the rural population (IRENA 2015), is underdeveloped in the rural and remote areas. Even those having access find it unreliable and expensive for irrigation. Fuel-powered motorized pumps are expensive for smallholders given high fuel and maintenance costs (de Fraiture and Giordano 2014; Namara et al. 2014; Mendes et al. 2014). Hence, an affordable and reliable energy source is vital for developing irrigation in small farms.

Due to the increasing cost of fuel (petrol and diesel) and the year-round availability of sunshine, we argue that making solar pumps widely available for irrigation is a promising option. Ghana receives daily solar irradiation of about 4-6 kilowatt hours per cubic meter (kWh/m^2) with corresponding sunshine for 6-8 months annually, especially in the northern part of the country (IRENA 2015). However, access to solar irrigation systems is limited. New approaches are needed to expand farmers' access to solar pumps that are appropriate in cost and scale. This study assesses the feasibility of solar irrigation for smallholders by integrating elements of business planning and business models with a suitability mapping approach adapted from Otoo et al. (2018). Suitability mapping takes into account the biophysical enabling environment required to scale out irrigation. Using the elements of a business model and suitability mapping approaches, the study develops and evaluates potential business options for the adoption of solar irrigation by smallholder farmers in Ghana. It uses data from existing solar photovoltaic (PV) irrigation systems, a literature review and interviews conducted with key industry actors.

The next section *Solar Technology, Groundwater and Irrigation in Ghana* provides an overview of the status of solar irrigation as well as a review of what is known about groundwater availability in Ghana. The section *Business Model and Suitability Mapping Approaches* explains the business model and suitability mapping methodologies. The results of suitability mapping are presented in the

[1] For labor force data, visit https://tradingeconomics.com/ghana/employment-in-agriculture-percent-of-total-employment-wb-data.html (accessed August 10, 2020).

section *Analysis: Suitability Mapping for Solar Pump Irrigation*. The section *Institutional, Policy and Regulatory Context for Solar Photovoltaic Irrigation* analyzes the policy and regulatory framework and how it affects the uptake of solar PV irrigation, and also highlights some environmental risks that must be managed. The section *Financial Analysis of Two Solar Irrigation Business Cases* presents a financial analysis of two business cases: (a) direct funding of an agribusiness; and (b) a cooperative model. Three business model scenarios are presented in the section *Business Model Scenarios for Upscaling Solar Photovoltaic Irrigation in Ghana*. Concluding remarks and recommendations emerging from the study are presented in the final section.

Solar Technology, Groundwater and Irrigation in Ghana

Solar Irrigation Technology is Beginning to Gain Traction

Solar-powered pumps using PV technology can be an economically and environmentally sustainable alternative to fossil fuel-powered pumps (Closas and Rap 2017). This technology can decouple irrigated agricultural growth from fossil fuel use. The benefits of solar PV irrigation systems include the potential for distributed, independent, off-grid power supply for both on-farm and household use by farmers in remote areas (Meah et al. 2009; Closas and Rap 2017). Small-scale solar irrigation could lead to improved incomes for farmers from the sale of produce, as well as improved nutrition (Burney et al. 2010). Solar pumps also have the added advantage of longer lifetimes with lower maintenance costs compared to fossil fuel pumps (Kolhe at al. 2002; Wazed et al. 2018).

In Ghana and other parts of sub-Saharan Africa, solar technology is slowly emerging as an alternative or a complement to grid-based electricity. Governments, development agencies and the private sector, realizing the potential benefits, have spurred interest in solar PV technology by launching several initiatives. For example, the African Development Bank is supporting the Scaling-up Renewable Energy Plan (Climate Investment Funds 2015), which includes a substantial investment in solar energy. Similarly, under the irrigation component of the Energising Development (EnDev) program,[2] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) is supporting small-scale farmers to access and use solar PV pumps for irrigation. The Power Innovation in Commercial Agriculture (PICA) project,[3] co-funded by the United States Agency for International Development (USAID) and Integrated Water and Agricultural Development (IWAD) Ghana Limited, has installed a solar energy generation capacity of 0.8 megawatt peak (MWp) targeted at benefiting 300 smallholder farmers in northern Ghana. Similarly, NewEnergy (a nongovernmental organization [NGO] in the country), has installed solar-powered irrigation systems in four communities in northern Ghana, with financial support from the United Nations Development Programme (UNDP) and the Energy Commission, Ghana. Further, GIDA is converting the electric pumps at existing irrigation schemes to solar-powered pumps.

Until recently, Ghana's PV generation capacity lagged behind that of other African countries such as Kenya and Zimbabwe (Bawakyillenuo 2012). That said, Ghana's grid-connected solar PV capacity of 1.92 MWp from the Navrongo plant was second only to that of Cape Verde's 6.4 MWp in West Africa, as of 2013 (REN21 2014). Ghana has since added a 20 MWp plant at Gomoa Onyandze in the Central region (Energy Commission 2016). According to the new Ghana Renewable Energy Master Plan (Government of Ghana 2019), as of the end of 2015, more than 10 MWp of stand-alone solar PV systems had been installed. While this reflects rapid growth, total off-grid installed solar capacity in Ghana remains much lower than that of Senegal and Nigeria at 21 MWp and 20 MWp, respectively (REN21 2014).

Solar PV technology is still mostly used in service sectors such as telecommunications, rural health, street lighting and water supply installations. Its use in the agriculture sector remains limited (Amankwah-Amoah and Sarpong 2016). Specific data on the number of solar pumps in Ghana are unavailable. However, irrigation is clearly one of the most promising areas for application of solar energy, particularly in the Northern Region, where there is a unimodal rainfall regime with a long dry season and high demand for irrigation.

Smallholder Irrigation in Ghana

Informal irrigation, i.e., small-scale or farmer-led irrigation, initiated and developed by private entrepreneurs and farmers, is expanding at a rapid rate in Ghana with improved farmer access to, and adoption of, various water-pumping technologies (Namara et al. 2011, 2014). Farmers use buckets or watering cans,

[2] https://energypedia.info/wiki/Solar_Pumps_for_Irrigation-_The_Success_of_EnDev_Approach_in_Ghana
[3] https://partnerships.usaid.gov/partnership/power-innovation-commercial-agriculture

diesel/petrol/electric pumps, and gravity for both lifting water and field application. Bucket irrigation is the most common, but many smallholder farmers are investing in motor pumps (de Fraiture and Giordano 2014; Namara et al. 2011). Farmers often combine the use of buckets and pumps, depending on the stage or type of cropping as well as the relative costs of fuel or hiring pumps (Namara et al. 2014). Due to the high cost of purchasing irrigation pumps, smallholders turn to low-cost small kerosene or diesel pumps imported from China. These pumps lack durability and require frequent servicing or replacement, thereby increasing costs (de Fraiture and Giordano 2014).

Currently, most irrigation water is drawn from surface water. Only about 20% of irrigation utilizes groundwater sources (de Fraiture and Giordano 2014; Siebert et al. 2010). Yields and income are generally higher for farmers using shallow groundwater than for canal irrigators (Namara et al. 2014; Dittoh et al. 2013). As such, groundwater irrigation is becoming more common in some areas (Namara et al. 2011). Along the coast, shallow hand-dug wells (1-5 m depth) can provide water for year-round irrigation of cash crops on small farms (Obuobie and Barry 2012; Agodzo et al. 2003). In drier northern Ghana, smallholder irrigation using groundwater draws mainly from shallow alluvial aquifers, irrigating 0.04-0.1 ha per farm (Kortatsi 1994; Obuobie et al. 2013). Most produce is sold in domestic markets, particularly larger towns and cities (Drechsel et al. 2006).

The continued growth of irrigated production in Ghana will depend on expanding the availability and productivity of small-scale irrigation technologies. At present, the laboriousness of bucket-based lifting and application limits farmers to small cultivated areas (Woltering et al. 2011), particularly during the dry season in the northern areas where labor shortages are a major constraint (Obuobie et al. 2013). Pumps need less labor and enable production on larger areas, but petrol and diesel pumps are expensive to operate and have negative environmental externalities (Namara et al. 2011). Solar energy can, therefore, be a more reliable and affordable source of energy, potentially increasing efficiency, incomes and agricultural production. However, private sector actors—from technology suppliers to farmers—need to be incentivized to invest in solar PV irrigation.

Interest in using solar pumps is growing, largely due to increasing fuel prices, frequent machinery breakdowns and increasing maintenance costs of motor pumps. Farmers have shown an interest in solar pumps, provided they are available at an affordable price. Solar pumps could provide a clean and sustainable energy solution for lifting water for irrigation. With an effective policy and institutional support system, provision of a market-based solar-powered irrigation service could be a viable business.

Groundwater Resources in Ghana

Ghana has been described as a country having 'high irrigation potential but variable aquifer suitability' (Pavelic et al. 2013). Although there is great potential for solar-powered irrigation using groundwater (as shown in the section *Analysis: Suitability Mapping for Solar Pump Irrigation*), sustaining aquifers over the long term is a serious challenge. Parameters such as recharge rate and static and dynamic head, which can vary greatly from one location to another, must be determined for an accurate configuration of the pump (Fedrizzi et al. 2009). How these parameters fluctuate with time at a location also needs analysis. Unfortunately, there has been very little research on groundwater levels and recharge patterns in Ghana. This is also the case even in northern Ghana, where there is a heavy reliance on groundwater but aquifers are typically limited and restricted (Tay and Kortatsi 2008; Lutz et al. 2015; Obuobie et al. 2018).

Research findings on sustainable groundwater irrigation potential in the dry areas of northern Ghana have been varied. One study in two districts of the Upper East Region found there is potential to expand dry-season irrigation from groundwater 14- to 18-fold (Obuobie et al. 2013). Anayah et al. (2013) also found that existing recharge rates would enable considerable expansion of dry-season irrigation in the Northern Region. Estimates of groundwater production in relation to average annual recharge suggest that total abstraction from Ghana's aquifers is less than 2% of annual recharge, although localized cases of over-abstraction and extreme drawdown may occur (Martin and van de Giesen 2005; Lutz et al. 2007).

However, other studies suggest caution. For example, Lutz et al. (2015) estimated the recharge rates of four boreholes near Tamale to be approximately 5% of precipitation, which is in line with other estimates (Martin and van de Giesen 2005; Martin 2006; Obuobie 2008). Over a seven-year period, this study observed a net reduction in groundwater levels at all the study sites. Notably, the largest decline of 3 m was at the only site with a solar pump. At the other three sites fitted with hand pumps, the decline ranged from 0.4 m to 0.9 m (Lutz et al. 2015). Anim-Gyampo et al. (2012) developed a method for calculating safe yield, defined as the long-term balance between the amount of groundwater abstracted and the amount of recharge. They found that, of the 28 boreholes studied in Kassena-Nankana district in the Upper East Region, seven were already overexploited and two were likely to reach the level of overexploitation within 30 years (Anim-Gyampo et al. 2012).

Growing mechanization can perpetuate a cycle of rising demand for groundwater and energy, as seen in India and other countries (Shah 2009; Wada et al. 2012). This suggests that Ghana should balance effective groundwater assessment and management arrangements with limits on pump capacities and the provision of solar pump subsidies (Closas and Rap 2017). Solar irrigation pumps have the potential to accelerate aquifer depletion more rapidly than petrol, diesel or grid-supplied electric pumps. The reason is that solar operating costs are nearly zero while fuel costs are very high. With solar-powered pumps, there is no incentive to minimize pumping. As the number of solar PV pumps increases, this will become a major challenge. Reducing the incentive to overpump can be addressed in several ways. One option is to encourage solar pumping service providers. Another is to support alternative uses of the power generated by solar panels – recharging batteries or running other machinery, for example. In future, even selling power to the utility grid may become feasible, an approach that is being implemented in India (Shah et al. 2018).

Business Model and Suitability Mapping Approaches

Business Model Framework for Solar Photovoltaic Irrigation Systems

This study takes elements of business planning and business models and analyzes these in the context of smallholder irrigated agriculture. In particular, we assess the viability of solar PV technology for irrigation in Ghana and develop plausible business models with potential for scaling up. The usefulness of a business model depends on the specific value proposition, the nature of the good/service under consideration, and the business environment, such as competition, prices and institutional factors. Within the irrigation sector, development of sustainable business models for solar PV irrigation systems requires a consideration of economic and environmental factors within a specific policy and institutional context. Figure 1 outlines a business model framework developed by Otoo et al. (2018) for solar PV irrigation that includes integrating components on: (i) suitability mapping; (ii) environmental sustainability; (iii) institutional, policy and regulatory context; (iv) finance mechanisms; (v) technology supply chain; and (vi) economic sustainability.

In this framework, suitability mapping of the biophysical resources of an area for solar PV technology and environmental sustainability are critical parameters for developing context-specific business models. Limited bioresources would mean that solar PV for irrigation would not be possible. The consideration of environmental sustainability too is particularly important as cheaper and more powerful solar PV pumps can result in significant environmental costs related to groundwater extraction and water quality. In addition to the biophysical aspects, development of sustainable business models for solar PV technology requires understanding the existing institutional, policy and regulatory context, finance mechanisms and technology supply chain. Detailed descriptions of these components can be found in Otoo et al. (2018).

Data for Business Model Development

The data used in this report are drawn from reviews of gray and published literature, focus group discussions, structured questionnaires, key informant interviews and policy documents. The solar PV technology supply chain mapping is based on open-ended interviews conducted with five industry stakeholders involved on the input side, including two solar pump and panel importers, two government departments and one technology implementer. Key informant interviews were conducted with the Managing Director of Pumptech, an authorized distribution partner for LORENTZ solar pumps, and with the Chairman of NewEnergy, a Ghanaian NGO engaged in implementing solar PV technology for irrigation. Two business case studies were identified and selected in consultation with the Project Manager for Energy and Finance for Irrigation at the Energy Commission: (i) direct funding to an agribusiness, and (b) a cooperative model. These business cases may not be representative of the entire country, but they do provide useful insights into business models for solar irrigation in Ghana.

Suitability Mapping

In addition to assessing economic feasibility and sustainability, the study also analyzed the spatial suitability of using solar pumps for surface and shallow groundwater irrigation. We developed suitability maps for solar pump irrigation using a combination of biophysical indicators representing the natural environment and market access following a methodology outlined by Schmitter et al. (2018). The framework looks at current agricultural land and identifies locations where solar PV technology could transform rain-fed agriculture or replace diesel pumps or other pumping technologies in irrigated agriculture.

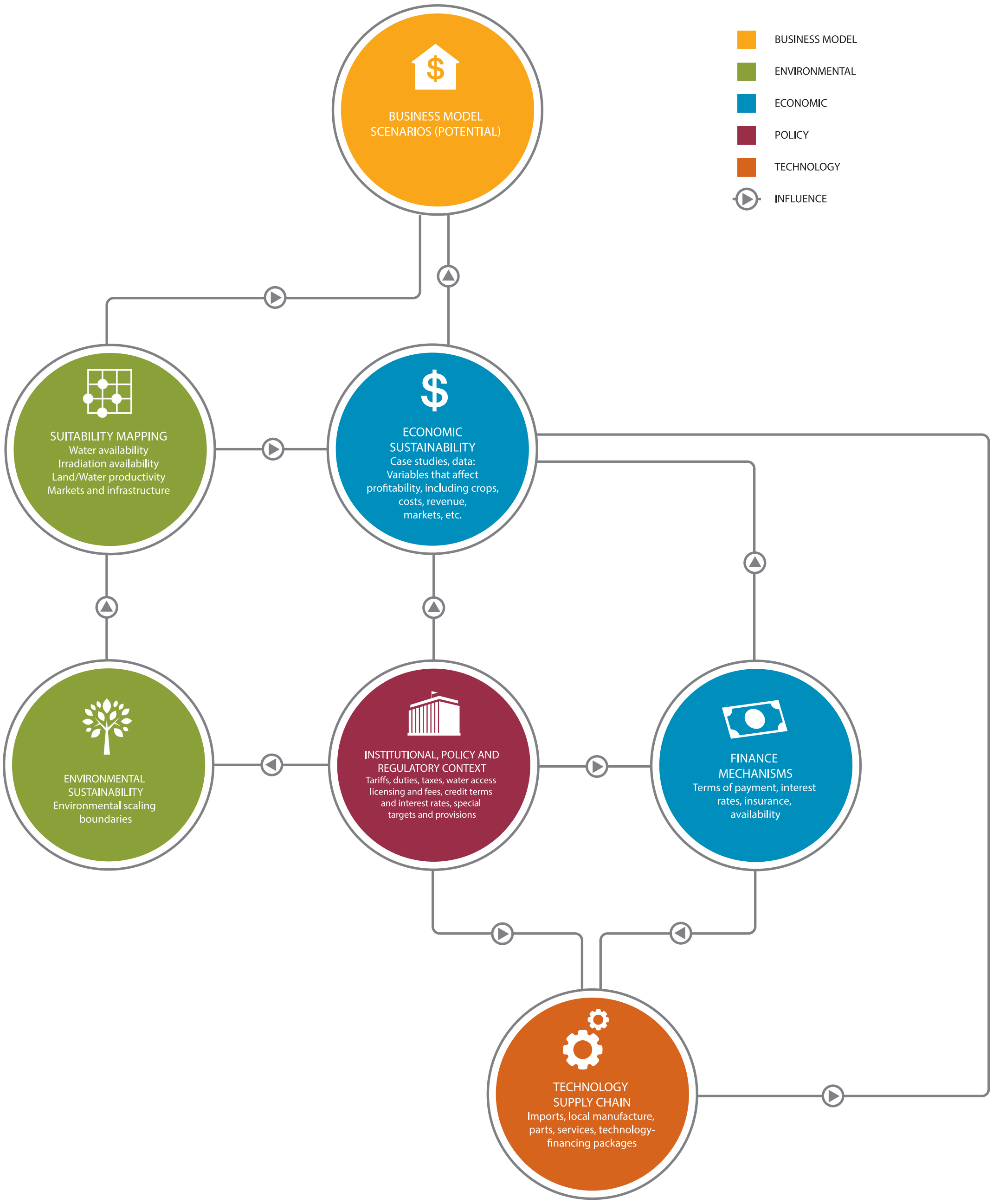

Figure 1. Conceptual framework for development of business models for solar-powered irrigation.
Source: Otoo et al. 2018.

The framework was adapted to Ghanaian conditions. Some of the key adjustments made were: (i) replacement of input maps for Ghana, (ii) inclusion of a travel time to markets layer to reflect the poor road infrastructure, and (iii) inclusion of wetland information to safeguard water bodies. We also adjusted the weighting factors. The travel distance to markets in bigger cities is a proxy for input and output markets. However, it does not include specific commodity markets. Consequently, the mapping does not take into consideration market saturation for particular commodities. The maps could be used by solar PV technology suppliers to identify potential agricultural areas to develop supply chains and services.

Five categories of data were used: (i) topography and soil suitability; (ii) climate; (iii) surface water and groundwater resources; (iv) land use and protected areas; and (v) road infrastructure and travel time to major towns (see Annex 1).[4] Each of these categories show the suitability of irrigation investments in general. Adding the eight-month period of high sunshine and solar radiation levels (about 4-6 kWh/m^2), especially in the dry season in northern Ghana, focuses the findings specifically for solar irrigation.

[4] All the data used in the analysis are open source. The highest available spatial resolution was downloaded, with the exception of the digital elevation model, for which 90 m was selected to reduce computation time.

This methodology can be used to assess the suitability of an area for solar energy-based irrigation using various combinations of solar pump models that differ in solar irradiation requirement, dynamic head and available water resources (surface water and groundwater at different depths). Taking into consideration smallholders' access to land and affordability, two specific solar photovoltaic pumps were selected: one with a minimum solar irradiation threshold of 0.5 kWh/m² and a lift capacity of up to 7 meters (m); and the other with a threshold of 1 kWh/m² and a lift capacity of up to 25 m (Global LEAP Awards 2019). Based on these specifications, suitability was assessed for five different available water sources (Table 1).

Table 1. Solar irrigation suitability mapping for five different available water sources.

i.	Shallow groundwater up to 7 m (0-7 m)
ii.	Groundwater up to 25 m (0-25 m)
iii.	Surface water only (proximity to rivers and the potential of small reservoirs)
iv.	Combination of surface water and groundwater up to 7 m
v.	Combination of surface water and groundwater up to 25 m

Four steps were followed: (i) constraint analysis; (ii) reclassification of input maps; (iii) assigning weighting factors to each reclassified map; and (iv) development of suitability maps using the constraint analysis under various modalities of water resource availability.

Constraint analysis: The variables considered for the constraint analysis are those that are assumed to restrict the feasibility of solar energy-based irrigation (Table 2). For example, protected areas (e.g., natural forests, parks) or areas with steep slopes are considered unsuitable. The slope constraint was set at 8% to reduce the challenges of potential soil erosion due to irrigation development. Areas restricting support for solar-powered irrigation are excluded from further consideration in the constraint analysis.

Table 2. Criteria for exclusion of areas unsuitable for solar pump irrigation.

Map	Constraint (excluded areas)
Depth to bedrock	Depth to bedrock less than 60 cm
Land cover	Land cover excluding agriculture, grassland, shrub land and bare land
Protected areas	All protected areas: wetlands, national parks, wildlife conservation areas
Slope	Areas of slope greater than 8%
Roads	Distance to roads greater than 5 km

Source: Adapted from Schmitter et al. 2018.

Reclassification of input maps: the input maps were reclassified into five suitability classes with 1 representing the least suitable areas and 5 representing highly suitable areas (Table 3). A conservative approach was used in the classification. As such, low suitability areas were set as constraints. This was necessary since the results of the mapping were highly dependent on the criteria set for solar-powered irrigation. For example, if an area with aquifer productivity below 0.1 liters per second (l/s) was classified as low suitability while all other criteria were highly suitable, the overall suitability would have been good. However, solar irrigation at this location would not be successful due to low aquifer productivity.

Assigning weighting factors to each reclassified map: Weights were given to each reclassified input map using the Analytic Hierarchy Process (AHP)[5] or the Saaty Method (Saaty 1977) used for similar agricultural suitability analyses (Yalew et al. 2016; Owusu et al. 2017). The analysis was carried out for different available water sources (Table 1), which resulted in a different order of importance of the input maps as a function of the water resources considered (Table 4).

[5] A pairwise comparison of each input relative to all other inputs is carried out using a 9-point reciprocal scale. Thus, when comparing 'A' to 'B', if 'A' is moderately more important than 'B' and thus given 3 points, then when comparing 'B' with 'A', 'B' would be considered moderately less important than 'A', i.e., 1/3. The result is a nxn matrix ($A=a_{ij}$) of ratings, where n represents the number of inputs.

Table 3. Reclassification criteria used for various maps included in the multi-criteria analysis.

Factor	Highly suitable	Suitable	Moderately suitable	Less suitable	Least suitable	Unsuitable
Slope (%)	0-2	2-4	4-8			> 8
Solar irradiation (kWh/m²)	2,500-3,000	2,000-2,499	1,750 -1,999	1,500-1,749	1,300 -1,499	< 1,300
Proximity to surface water (small reservoirs, wetlands or rivers) (m)	< 50	50-150	150-250	250-500	> 500	-
Groundwater depth (0-7 m) Groundwater depth (0-25 m)	0-7 0-7	- 7.1-25	- -	- -	- -	> 7 > 25
Aquifer productivity (l/s)	> 0.5	0.1-0.5	-	-	-	< 0.1
Groundwater storage (mm)	> 25,000	10,000-25,000	1,000-10,000	-	-	< 1,000
Travel time to town with population > 100,000 (hours)	< 2	2-4	4-6	6-8	8-24	> 24

Note: Highly suitable = 5; Suitable = 4; Moderately suitable = 3; Less suitable = 2; Least suitable = 1; Unsuitable = Null.

Table 4. Weighting factors derived for three different scenarios following the Analytic Hierarchy Process (AHP).

	Groundwater		Surface water
Factor	Groundwater ≤ 7 m	Groundwater ≤ 25	Surface water and small reservoirs
Solar irradiation (kWh/m²)	0.278	0.278	0.296
Slope (%)	0.101	0.101	0.131
Groundwater depth (0-7 m)	0.262	-	-
Groundwater depth (0-7 m, 7.1-25 m)	-	0.262	-
Aquifer productivity (l/s)	0.158	0.158	-
Groundwater storage	0.158	0.158	-
Proximity to river	-	-	0.258
Small reservoirs	-	-	0.258
Travel time to markets (hours)[a]	0.043	0.043	0.057
Consistency ratio[b]	0.013	0.013	0.01

Notes:

[a] Travel distance to towns with a population larger than 100,000 is considered.

[b] Consistency ratio = consistency index/random index following Saaty (1977).

Development of suitability maps using the constraint analysis under various modalities of water resource availability: The weighted maps were aggregated to create suitability maps for two groundwater and one surface water resource conditions at 250 m resolution. For suitability scenarios which included groundwater and surface water, the maximum suitability value was taken following an overlay of the suitability using groundwater at 7 m or 25 m with the suitability for surface water. The five maps were then reclassified into highly suitable (class 5: 4.5-5), suitable (class 4: 3.5-4.5), moderately suitable (class 3: 3.0-3.5), less suitable (class 2: 2.0-3.0) and least suitable (class 1: 1.0-2.0) classes with values below 1.0 being considered as unsuitable. The final suitability maps only consider areas that are highly suitable, suitable or moderately suitable.

The predicted areas for solar irrigation under various water resource conditions were compared with the suitability maps for small reservoirs and small water-lifting pumps in Ghana developed by the Food and Agriculture Organization of the United Nations (FAO) (FAO 2012).

Analysis: Suitability Mapping for Solar Pump Irrigation

Suitability Mapping for Solar Photovoltaic Irrigation

Constraints

Identifying constraints is critical to estimating the potential for solar PV pumps. Figure 2 shows that the most limiting constraints to using groundwater-only sources in Ghana are: (i) groundwater storage, which carves out the Middle Eastern portion of the country; (ii) land use, which is forested in the central part of the country; and (iii) distance to roads, which are sparse in the central part of Ghana. When surface water is the only source of water, proximity to rivers, wetlands or small dams is the limiting constraint. While groundwater storage cannot be changed, there is room for increasing the solar PV potential, especially in the north to central parts of the country, by improving the road networks and related infrastructure, e.g., construction of more small reservoirs.

Suitability Maps

This section presents the results of suitability mapping for various water resource conditions at a resolution of 250 m, aggregated at regional and district levels (Figure 3). Irrespective of the water source, there are no 'highly suitable' or 'least suitable' areas in Ghana. In other words, there is no area in Ghana where all criteria are optimal. In instances where groundwater up to 25 m is considered, most of the suitable areas fall within the 'suitable' category (class 4), i.e., most of the input parameters are favorable. When considering only surface water, suitability drops significantly for many areas to 'less suitable' (class 2) or 'moderately suitable' (class 3) due to the limited distance allowed from water bodies (500 m). As a result, when combining water resources, areas that were less suitable for surface water-based solar irrigation end up being 'upgraded' to the 'suitable' or 'moderately suitable' categories.

Overall, the locations found to be suitable for solar PV pumps are mainly in areas with groundwater. These areas consist of locations that are currently irrigated by various irrigation technologies (solar, diesel or electric pumps) and new areas that could be potentially developed for solar energy-based irrigation. Differentiating between these two types is currently not possible because data on the areas presently irrigated using solar power are not readily available or reliable. Considering shallow groundwater up to a depth of 25 m, there is a potential area of 1.8 Mha that is moderately suitable or suitable for solar energy-based irrigation. The total area suitable for solar-powered surface water irrigation is much lower, around 700,000 ha. When the two sources, groundwater and surface water, are combined, this area increases by 27-50%. For example, considering groundwater up to a depth of 25 m and surface water increases the suitable area to approximately 2.3 Mha, which is slightly higher than most estimates.

The regional breakdown of suitability for solar-powered pumping for various water resource conditions is shown in Table 5. The Northern Region has the largest potential (moderately suitable to suitable) area for solar-powered irrigation, while the Western North Region does not have any areas suitable for solar irrigation using groundwater. This divergence can be attributed to the different land use and land cover types across these two regions and generally between northern and southern Ghana; while the former is characterized by grassland and shrubland, the latter falls within the forest belt of Ghana. The Central, Ahafo, Brong Ahafo and the Western regions also have very little suitable area when considering only groundwater (< 6,000 ha), or both surface water and groundwater (< 21,000 ha).

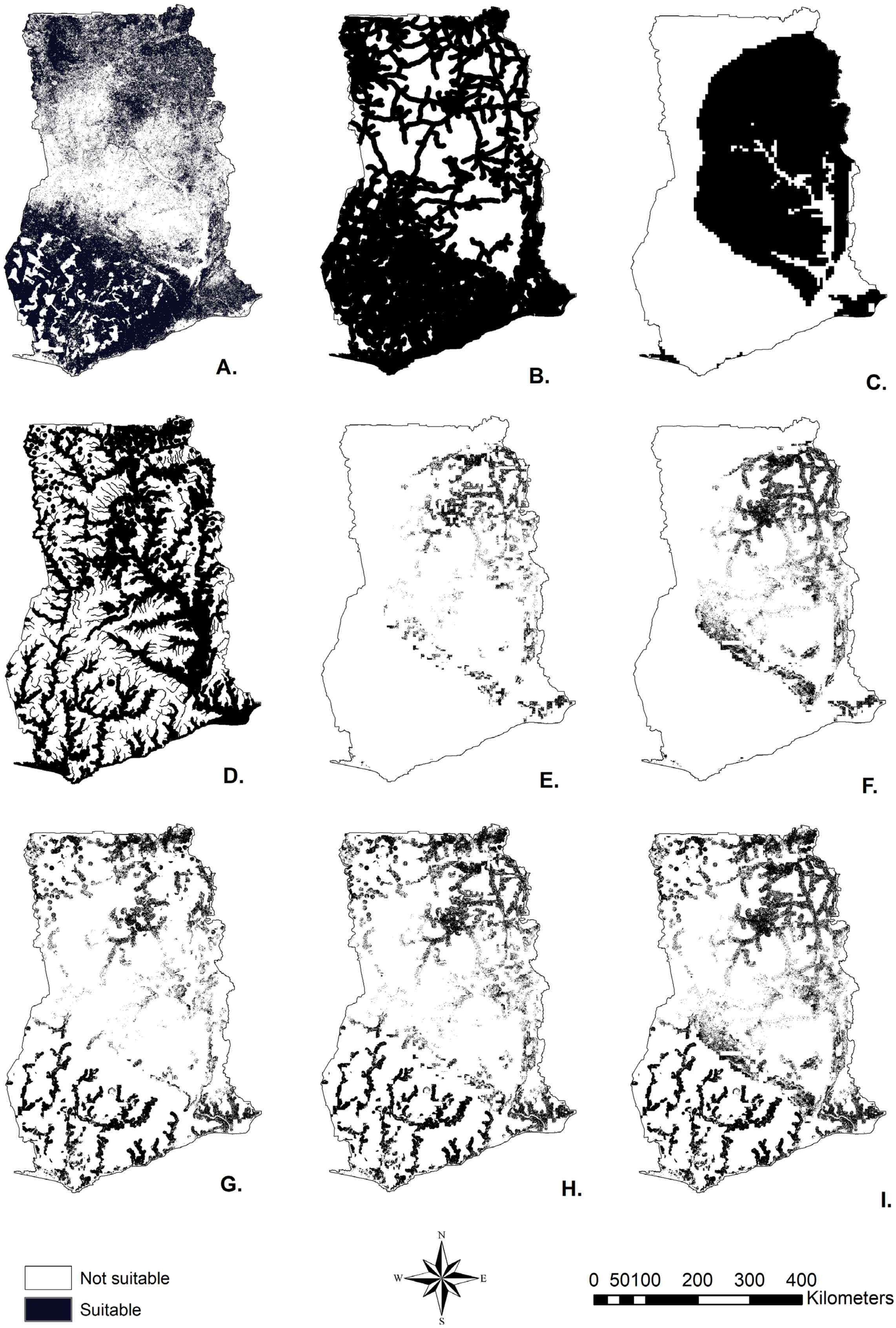

Figure 2. Main input maps (A, B, C and D) and final constraint maps (E, F, G, H and I) to assess areas suitable for solar PV pumping.

Notes: A. Land use/land cover constraints. B. Proximity to roads constraints. C. Groundwater storage constraints. D. Surface water constraints. E. Final constraint for groundwater up to 7 m depth. F. Final constraint for groundwater up to 25 m depth. G. Final constraint for surface water. H. Final constraint for groundwater at 7 m and surface water. I. Final constraint for groundwater up to 25 m and surface water.

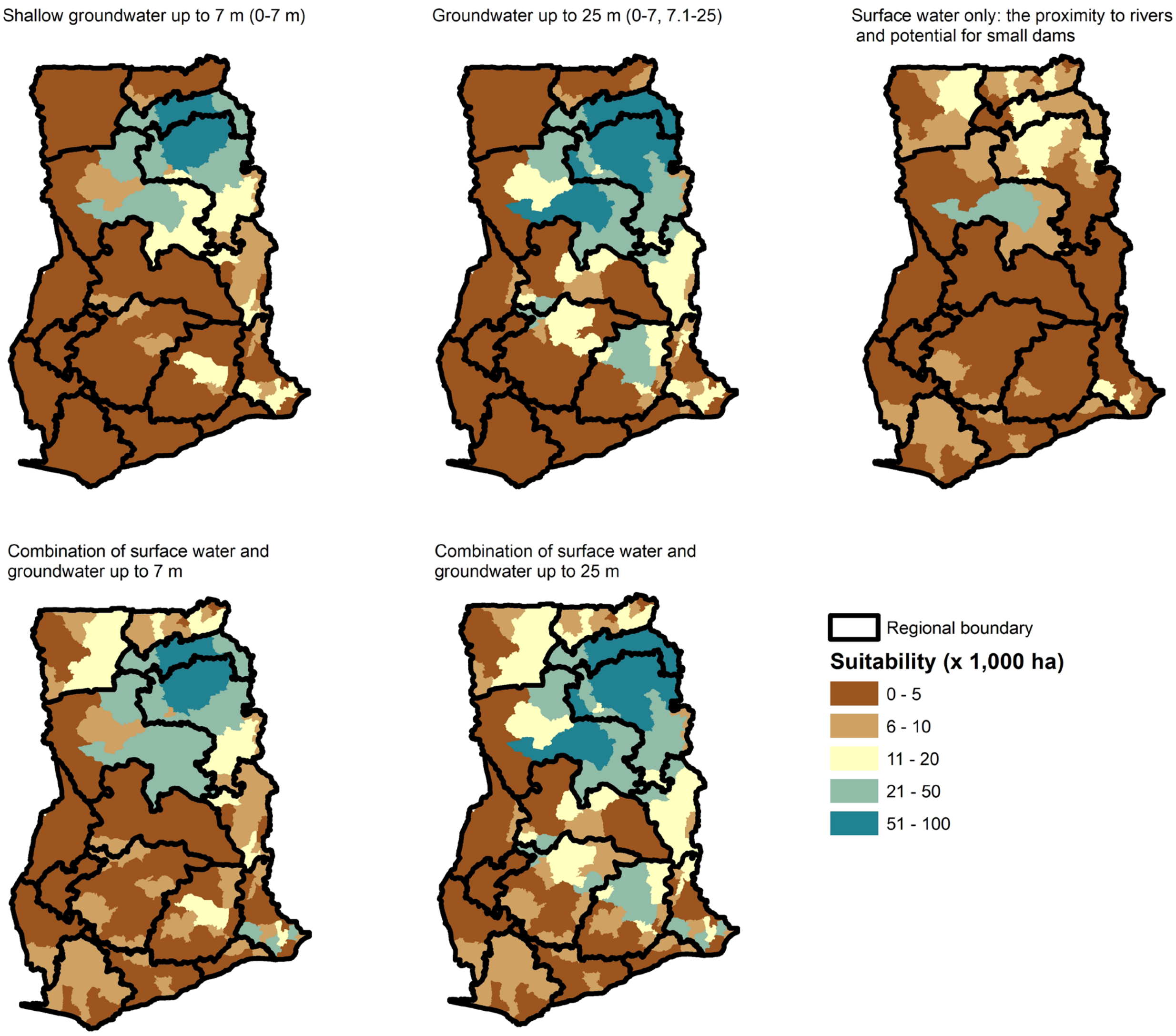

Figure 3. Suitability (x 1,000 ha) for solar energy-based irrigation for all five water resource conditions considering only the suitable (class 4: 3.5-4.5) and moderately suitable (class 3: 3.0-3.5) classes.

These solar suitability results were compared with the suitability assessment for small motorized pumps carried out by FAO (FAO 2012). Overall, 54-69% of the suitable area was in agreement between the two studies. The FAO study only identified areas in the northern part of Ghana (Northern, North East, Upper East and Upper West regions) as being suitable for small reservoirs. Considering only these areas, 46% of those identified as suitable for small reservoirs would also be suitable for solar irrigation. Further, comparison with the groundwater potential assessment conducted by Gumma and Pavelic (2013) indicates that over 99% of the suitable areas are located in moderate to very good groundwater potential zones. These potential groundwater zones are mostly located in the northern half of the country.

However, information available on the current status of pumping in northern Ghana, in particular whether resources are already overdrawn (see section *Solar Technology, Groundwater and irrigation in Ghana*) or whether water is of poor quality for irrigation (see subsection *Environmental Sustainability of Upscaling Solar Photovoltaic Irrigation*), is insufficient and inconsistent. The spatial data used in this assessment allows for a first rapid estimation of solar-powered irrigation at the regional or subregional level. Higher resolution data are required on groundwater and surface water availability prior to planning or developing solar irrigation investments to ensure that the available water resources are sufficient and can be sustainably used (see Lutz et al. 2015; Otoo et al. 2018: 16-19). Finally, efforts to minimize water pollution from agriculture must accompany large-scale expansion of solar irrigation (subsection *Environmental Sustainability of Upscaling Solar Photovoltaic Irrigation*).

Table 5. Suitability for farmer-led solar-powered irrigation development[a] (x 1,000 ha) at the regional level in Ghana as a function of the availability of different water sources considering only the suitable and moderately suitable classes.

Region	Groundwater ≤ 7 m	Groundwater ≤ 25 m	Surface water and small reservoirs	Surface water, small reservoirs and groundwater ≤ 7 m	Surface water, small reservoirs and groundwater ≤ 25 m
Greater Accra	8	11	25	30	33
North East	223	313	41	230	314
Upper West	3	3	54	57	57
Upper East	11	22	87	97	107
Savannah	85	150	40	97	155
Brong Ahafo	2	6	16	18	23
Ahafo	0	1	21	21	21
Bono East	22	77	8	27	78
Volta	100	120	66	136	153
Oti	57	123	11	63	125
Ashanti	37	151	73	106	217
Central	0	1	49	49	50
Western	3	5	55	56	57
Western North	0	0	33	33	33
Eastern	71	169	56	121	215
Northern	427	648	94	442	648
Total	1,049	1,800	729	1,583	2,286

Note: [a] Areas with total solar irrigation potential, including areas that are currently under solar irrigation and potentially new areas that could be irrigated using solar technology.

Institutional, Policy and Regulatory Context for Solar Photovoltaic Irrigation

The suitability maps presented in the section *Analysis: Suitability Mapping for Solar Pump Irrigation* show that solar technology could be a promising solution to lift water for irrigation in Ghana. This section analyzes the extent to which the institutional, policy and regulatory context facilitates achieving the solar irrigation potential and identifies the additional steps that are needed to achieve this potential. Policies such as subsidies and fiscal incentives can be effective in attracting private sector investment (Brahm 1995; Zee et al. 2002), but they need to be supported with adequate financial resources and implemented by skilled personnel (Amankwah-Amoah and Sarpong 2016). To date, solar PV technology has not been adopted nationwide in Ghana for productive uses. The International Renewable Energy Agency (IRENA) attributes this to high upfront costs, and lack of financing and awareness of potential uses (IRENA 2015). Much of this section is based on extant literature and policy documents, as well as interviews conducted with the Head of Renewable Energy and the Project Manager for Energy and Finance for Irrigation at the Energy Commission, Ghana.

The evolution of solar PV technology adoption in Ghana can be represented as five overlapping phases (Figure 4). Small-scale solar PV electricity started with installations by NGOs including churches, hospitals and some state-owned enterprises in the 1980s (Adanu 1994). A few international development agencies financed public solar PV electrification projects in the early 1990s (Amankwah-Amoah and Sarpong 2016; Obeng and Evers 2009). By that time, other sectors had also started adopting solar technology, for example, for home systems, vaccine refrigeration, telecommunications, schools, street lighting and pumping water (Amankwah-Amoah and Sarpong 2016; Bawakyillenuo 2012). By 2012, the government was promoting the use of environmentally friendly energy sources such as solar power for productive uses through the Sustainable Energy for All (SEforALL) initiative.

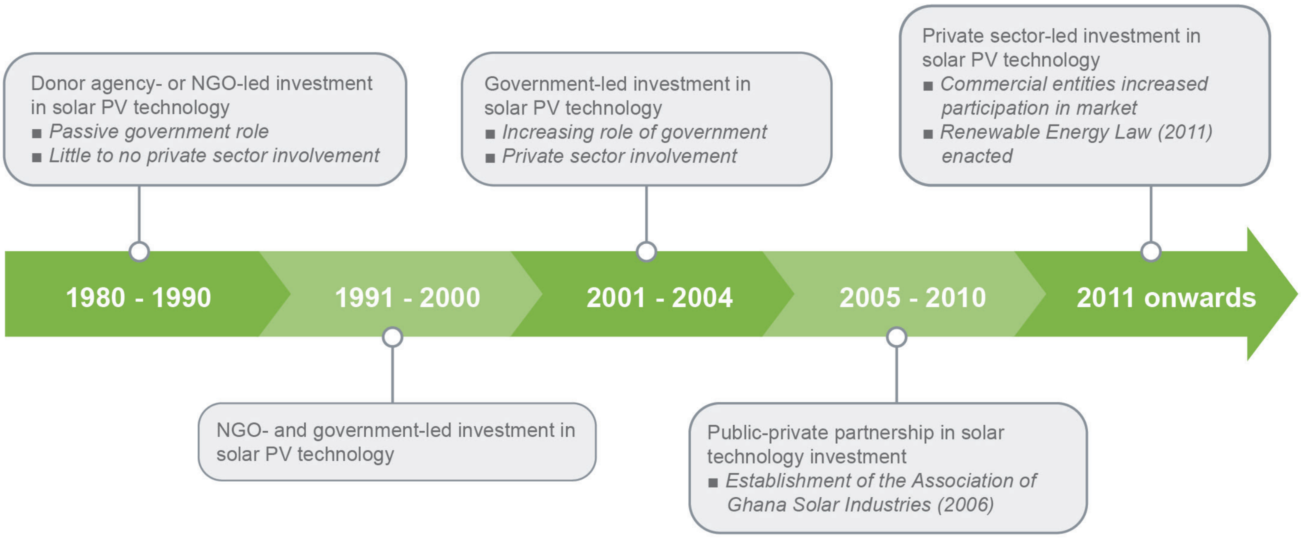

Figure 4. Phases in the expansion of solar PV technology use in Ghana.
Source: Adapted from Amankwah-Amoah and Sarpong 2016.

The number of solar PV systems increased from 335 in 1991 to more than 4,000 by 2003 (Obeng and Evers 2009). This was partly due to the implementation of the National Electrification Scheme, the aim of which is to extend reliable electricity supply to all parts of the country by 2020 (Energy Commission 2006). In the first phase, there were 335 PV system installations with an installed capacity of 160 kilowatt peak (KWp), targeted mainly at schools, hospitals and clinics. The second and third phases (1991-2004) saw the government playing an increasing role in solar power initiatives and some involvement by the private sector. During this period, the number of PV system installations grew to more than 4,000 with an installed power capacity of 1,000 kWp. These were mainly solar home systems; only 80 PV systems were used for water pumping. The government's strategy to increase the share of renewable energy (including solar energy) in the energy mix became clearer during the fourth and fifth phases, when the private sector began increasing its investments. Evidence of this was the establishment of the Association of Ghana Solar Industries in 2006. During this period, there were a number of larger installations, such as the Navrongo Solar Power Plant, which is a grid-connected solar PV system with a capacity of 1.92 MWp, and the Gomoa Onyandze plant with a capacity of 20 MWp (Energy Commission 2016). As of the end of 2015, more than 10 MWp of stand-alone solar PV capacity had been installed (Government of Ghana 2019). However, specific data on the number of solar pumps in Ghana are not available.

Evolution of Policies and Regulatory Framework

In 2011, the Renewable Energy Act was adopted to provide a regulatory framework and fiscal incentives to boost private sector investment in renewable, including solar, energy. Declining prices of solar panels in the global market further boosted demand and private sector investment. Currently, there are more than 100 vendors of solar PV technology licensed by the Energy Commission.

The Ministry of Energy and the Energy Commission together develop and oversee solar energy projects under the auspices of the international SEforALL initiative.[6] They recently launched a new private sector framework to promote installation of solar home systems, including solar-powered irrigation.

The *Ghana Shared Growth and Development Agenda II* (GSGDA II), the medium-term (2014-2017) policy framework for overall national development (NDPC 2015), was aimed at building a 'green' economy. The *Coordinated Programme of Economic and Social Development Policies 2017-2024* (Government of Ghana 2017) has replaced GSGDA II, but continues to support sustainable natural resource management, mainstreaming climate change resilience, and the expansion of renewable energy.

In addition, the National Climate Change Policy, launched in 2014, and the Intended Nationally Determined

[6] SEforALL "works with leaders in government, the private sector and civil society to drive further, faster action toward achievement of Sustainable Development Goal 7 (SDG 7), which calls for universal access to sustainable energy by 2030." (https://www.seforall.org/ - accessed on November 8, 2020).

Contribution aim to increase the uptake of climate-smart technologies (MEST 2012; Government of Ghana 2015). Solar PV irrigation is included within these policies, in that it addresses national development aims and is part of climate-smart agriculture.

The Renewable Energy Act provides the legal and regulatory framework for developing Ghana's renewable energy subsector by offering regulatory and fiscal regimes and attractive pricing mechanisms (Government of Ghana 2011). The Act establishes two policy instruments aimed at boosting renewable energy technology: the Feed-in Tariff and the Renewable Energy Purchase Obligation. Four incentive mechanisms established under the Act are in various stages of implementation. A Renewable Energy Fund was established to provide financial support for the development, promotion, use and sustainable management of renewable energy sources, but it is not yet operational. Under the feed-in tariff system, there is potential for those using solar energy for irrigation to sell the excess energy generated to serve off-grid rural populations and for the productive use of energy, such as for drying or refrigeration. This option, however, remains to be explored.

A key incentive for irrigated agriculture is the import tax exemption for solar PV systems. However, this incentive has so far had only limited impact: while solar panels are not taxed, associated equipment and accessories such as solar batteries and pumps are taxed. Solar panels constitute less than 50% of the cost of whole systems; therefore, there is no major cost saving due to this incentive.

The Food and Agriculture Sector Development Policy II (FASDEP II) (MoFA 2007) also addresses the need to develop new energy sources. One policy objective of FASDEP II is to enhance the production potential of existing irrigation schemes by raising the irrigation water productivity through, for example, developing alternative ways to supply water to irrigation schemes, including small-scale pumps and reducing energy costs. To date, although private sector investments have been increasing, these policies have not triggered rapid growth in the solar power market proportionate to its potential.

Institutional Context

Annex 2 provides a list of institutions involved in the renewable energy sector including the solar energy sector in Ghana. Among these, the Energy Commission is primarily responsible for the implementation of the Renewable Energy Act and is the technical regulator of Ghana's renewable energy industries (Energy Commission 2016). The Public Utilities Regulatory Commission (PURC) is responsible for setting tariffs for the purchase and transmission of electricity from renewable energy suppliers as per the Public Utilities Regulatory Commission Act 1997. Thus, PURC and the Energy Commission are the economic and technical regulators, respectively, of Ghana's energy sector (IRENA 2015). That said, household-level solar irrigation systems are not within this regulatory framework.

The Ministry of Sanitation and Water Resources is responsible, among other things, for facilitating private sector participation in providing improved technologies, including solar-powered irrigation technologies. The Environmental Protection Agency is responsible for protecting and improving the environment and for issuing environmental permits, including to the renewable energy sector. Other relevant organizations involved in the renewable energy sector include NGOs, research institutes, industry associations, and development and donor agencies (Annex 2).

Despite the large number of actors, the institutional and regulatory context of the solar energy sector in Ghana can be characterized as minimally supportive. Though institutions have their responsibilities outlined, some of the roles are only advisory; there is little emphasis on implementation. In addition, the key institutions emphasize supply to the grid rather than to individual users. Overall, the policies are not directly conducive to small-scale solar irrigation. It is, therefore, not surprising that a robust market has not emerged for solar pumps and related equipment in Ghana.

Solar Photovoltaic Technology Supply Chain

Within Ghana's solar PV technology supply chain (Figure 5), national distribution partners (NDPs) are entities that are certified by the manufacturer to import solar PV technology. The minimum requirements for NDPs include proof of availability of trained sales and technical staff, system installation experience with customer references, and a minimum number of systems installed per year to ensure familiarity with the technology. The manufacturers provide training to the NDPs on system specifications, installation and maintenance. Becoming an NDP requires establishing a relationship with, and clearance from, the manufacturer, and satisfying the in-country certification requirements of the Ministry of Sanitation and Water Resources and the Energy Commission.

The NDPs reach their end users directly or through their sales and service partners (SSPs), who engage in sales and installation, and provide after-sales support. The subsections *Manufacturing and Importing of Solar PV Systems, Distribution System,* and *End Users* elaborate, with specific examples, the key activities of each actor in the solar PV technology supply chain.

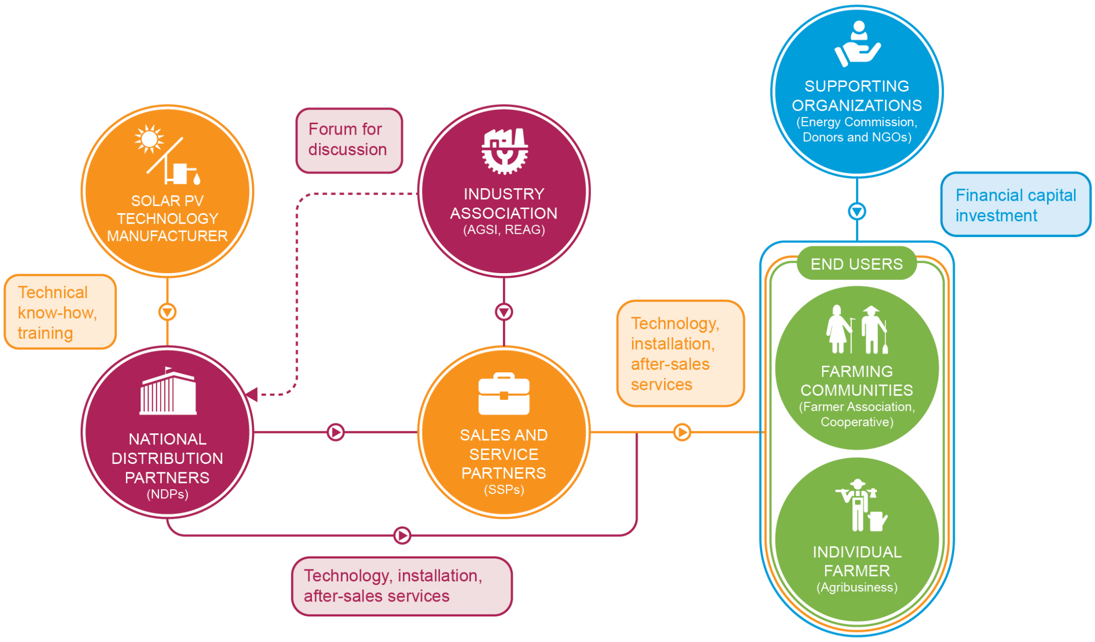

Figure 5. Supply chain for solar PV technology in Ghana.
Note: AGSI - Association of Ghana Solar Industries; REAG – Renewable Energy Association of Ghana.

Manufacturing and Importing of Solar Photovoltaic Systems

Currently, there are no solar pump manufacturers in Ghana. However, over 100 businesses are licensed by the Energy Commission to install and maintain solar systems. Two major foreign manufacturers have authorized NDPs to import and distribute their solar pumps: (i) Pumptech Ltd., which distributes LORENTZ solar pumps imported from Germany; and (ii) AKO Engineering Ltd., which distributes Grundfos solar pumps imported from Denmark. Pumptech has a strong reputation for supplying and installing solar water pumping systems nationwide, and has its main office in Tamale, the capital of the Northern Region. The company provides after-sales service and trains communities in the operation and maintenance (O&M) of solar pump systems.

Other importers and distributors include Hatoum Trading Co., distributor of Future Pumps made in India; Aggrico, a social enterprise promoting a portable ‘plug and play’ solar irrigation kit; and KickStart International, an NGO operating in several sub-Saharan African countries including Ghana, is testing low-cost solar irrigation pumps. These are the major companies operating in Ghana, but there are others which are now becoming active.

We have not been able to obtain consistent data on the prices of small solar pumps. According to the website of Future Pumps, its model SF1 costs USD 795 (GHS 3,500) in Ghana. This includes an 80 W panel, a 6 m high-quality suction hose, installation and a full two-year warranty. This pump is suitable for irrigating vegetable crops on an area up to 2 acres (0.8 ha). A similar portable Future Pump model (Sunflower) costs USD 650-750 in Kenya and comes with a five-year warranty (Merrey and Lefore 2018a).

Distribution System

NDPs have agreements with manufacturers to serve as national distributors and offer solar pumps at a price often predetermined by the manufacturers. They undertake sales and after-sales support, and train end users on O&M. They also administer a warranty to end users, which is typically for 2 years. To become an NDP, a company normally begins as a sales agent and, if successful for a year, can move to the next level as an SSP. The SSP can import pumps as a subsidiary to the NDP and can also become an NDP and have a direct relationship with the manufacturer.

SSPs facilitate the flow of goods and services from manufacturers through NDPs to end users. Currently, there are only a few SSPs in Ghana, e.g., three for LORENTZ pumps. Unlike the authorized NDPs, an SSP can add a margin to the purchase price of solar pumps. The LORENTZ pump SSPs can also import the technology as a subsidiary of an NDP. They engage in sales, installation and after-sales support to end users, but cannot administer a warranty. The NDPs use the SSPs to increase market reach, which nevertheless remains quite small. Donors, the government and NGOs fund most solar pumps installed on small-scale farms.

End Users

Solar pump end users include individual farmers and institutions with irrigation, industrial or community drinking water needs. Irrigation farmers usually access the technology through financial assistance from donor agencies, NGOs or the government. Direct unsubsidized sales to small-scale farmers are limited. Pumptech classifies end users into two types:

- Large-scale farmers who buy solar PV technology directly without donor support. These are mostly large plantation (20-100 ha) owners.

- Small-scale farmers having up to 2 ha of land who are predominantly supported by donors. They generally contribute 50-60% of the investment in kind (labor) or in cash.

In addition to installation and after-sales services, Pumptech also educates farmers on the benefits of using solar technology and its basic operation. Moreover, the company links up farmers with donors for financial assistance. Pumptech itself does not have a credit scheme for small-scale farmers—because of the high risk of default—but is in discussions with rural banks to design credit schemes for farmers. Banks hesitate as they are new to the technology and are not used to providing credit services for such technology.

Pumptech offers solar PV technology on credit for community water services, and believes this model has potential for irrigation too. Under this arrangement, the service provider purchases the technology on credit and uses it to supply potable water to communities. The water fees are used to repay the loan. This has been implemented in several sites. Pumptech believes that a similar irrigation water provider model could be viable but has not tested it. This model is found in other countries such as Senegal and Morocco, where a service provider assumes the technical, operational and financial risks and farmers purchase irrigation services (Merrey and Lefore 2018a).

Support Organizations along the Supply Chain

Other key players along the supply chain include donor agencies, NGOs, government institutions and industry associations. Development agencies such as GIZ and USAID in collaboration with the Energy Commission provide finance to farmers to acquire solar irrigation technology. Furthermore, several other institutions such as iDE, UNDP, the Energy Commission, NewEnergy, Ministry of Trade and Industry, and Accra Brewery Ltd. contribute to the promotion of solar irrigation pumps. Industry associations such as the Renewable Energy Association of Ghana and the Association of Ghana Solar Industries, in collaboration with manufacturers, provide training on the use of solar power. These industry associations aim to develop technology standards and provide a forum for discussion of current industry issues.

Finance Mechanisms for Solar Photovoltaic Technology for Irrigation

Financing is crucial for scaling out solar-powered irrigation. There are several potential financing options: self-financing, donor-supported finance and competitive loan markets. To facilitate farmers' access to finance, several donor-supported initiatives have been undertaken or are ongoing in Ghana. Merrey and Lefore (2018a) reviewed several financing innovations being tested in other African countries. Here, we discuss four plausible financing mechanisms for solar irrigation.

1. Public-private partnership
The government can and sometimes does collaborate with private actors in infrastructure development (e.g., roads, railways). This could be an appropriate approach in the initial stage of introducing a new technology. For example, GIDA, in collaboration with China Geo Engineering Corporation, supported farmers to install solar pumps at the Aveyime rice irrigation scheme. Similarly, the NGO NewEnergy, with support from the Ministry of Trade and Industry, is implementing a solar-powered drip irrigation project in partnership with Hikma Agro Services Limited and Pumptech Ltd.

2. Donor funding
International donors play a key role in promoting solar irrigation through subsidies, competitive calls and business incubation programs. For example, with support from UNDP, NewEnergy installed four solar-powered water pumping systems to irrigate over 12 ha of land cultivating vegetables, maize and fruit. It also installed a solar-powered irrigation pump in four farmer associations in the Northern Region of Ghana. This is one of our business case studies (see section *Business Case 2: Cooperative Model – The Case of the Datoyili Cooperative*).

3. Private sector funding
As part of their corporate social responsibility initiatives, a few private enterprises provide farmers with access to irrigation technology. Accra Brewery Ltd. has set up a solar-powered irrigation system for farmers at Tindongo in the Upper East Region. This GHS 80,000 (USD 18,180) investment is expected to benefit approximately 1,700 people.

4. Private sector-donor co-funding
There is considerable potential for co-funding by private sector and donor entities. USAID and IWAD Ghana Ltd., a private agricultural and irrigation development company at Yagaba, co-fund the PICA project for an irrigated nucleus farm and out-growers in the Northern Region. Similarly, GIZ has funded 40% of the solar technology for Groital Company Ltd., an agriculture company that is our other business case study (see section *Business Case 1: Direct Funding to Farmer – The Case of Groital Company Ltd.*). The remaining cost was raised from private equity.

These examples are not exhaustive; other African cases are discussed by Merrey and Lefore (2018a). Currently, most financing schemes for solar PV irrigation in Ghana are funded by donors and/or the government. The expectation is that as adoption of the technology spreads and awareness among irrigators increases, market-based approaches will gradually emerge, reducing the need for donor funds and/or government support. Indeed, donors and the government need to have an exit strategy to avoid dependency and political pressures to continue their subsidies.

Environmental Sustainability of Upscaling Solar Photovoltaic Irrigation

To assess the environmental sustainability of solar pumps, their impacts on greenhouse gas (GHG) emissions, water quantity and quality, and biodiversity must be considered. Here, we review some of the literature on this topic.

Greenhouse Gas Emissions

Current GHG emissions from sub-Saharan Africa account for a very small proportion of global emissions (Boden et al. 2011; World Bank 2016). Ghana's total GHG emissions are estimated at 6.2 million metric tons, with only 9.9% of this from the agriculture sector. Furthermore, emissions from diesel water pumps in 2010 were estimated to be less than 0.001% of the total emissions from the agriculture sector in Ghana. Even in the hypothetical scenario of every smallholder using a diesel pump, this would, at worst, increase to 0.034% (Sugden 2010). Nevertheless, widespread use of solar PV pumps will help maintain carbon emissions at their current low levels and reduce farming costs in the long term (Yue et al. 2014).

Water Quality

The section *Solar Technology, Groundwater and Irrigation in Ghana* has addressed the issue of aquifer sustainability. Groundwater in Ghana, to a large extent, meets World Health Organization (WHO) drinking water quality standards (Kortatsi 1994; Tay and Kortatsi 2007; Obuobie et al. 2018). Surface water quality, on the other hand, generally fails to meet WHO drinking water quality standards (Karikari and Ansa-Asare 2006; Abdul-Razak et al. 2009; Schäfer et al. 2009). Expanding irrigation will be accompanied by the increased use of fertilizers, veterinary medicines and pesticides, which may pollute water bodies. In the coastal areas, saltwater intrusion is an issue, e.g., in the Accra plains (Kortatsi and Jorgensen 2001; IGRAC 2009). Globally, nitrates from farming activities and animal waste are the most common pollutants in groundwater. There have been isolated cases of high nitrate concentrations in groundwater in Ghana (BGS and WaterAid 2004; Obuobie et al. 2018). Large-scale expansion of solar PV pumps, therefore, should be accompanied by efforts to minimize water pollution from agriculture.

Biodiversity and Natural Ecosystems

Solar PV pumping may lead to the expansion of agricultural lands, thereby threatening biodiversity. Over-abstraction and pollution of groundwater degrades ecosystems, particularly wetlands and estuaries. In Ghana, more than 80% of agricultural expansion during the period 1980-2000 resulted in loss of forest habitats; agriculture is identified as one of the main causes of habitat loss and pollution of coastal wetlands (MESTI 2016). Rather than extending agriculture to new areas, focusing irrigation investments on intensifying production on existing agricultural land combined with careful management of inputs may help minimize damage to the ecosystem and biodiversity.

Financial Analysis of Two Solar Irrigation Business Cases

This section analyzes two empirical solar irrigation business cases: (i) the case of Groital Company Ltd., involving direct funding to a farmer; and (ii) the case of Datoyili Cooperative, involving a cooperative model. These cases give an indication of the feasibility of two different approaches to developing solar-powered irrigation, as well as the commercial market potential for solar water-lifting technologies. They do not exhaust the possible business models. The financial viability of these two cases is analyzed in terms of the net present value (NPV), benefit-cost ratio (BCR) and internal rate of return (IRR).[7]

Business Case 1: Direct Funding to Farmer—The Case of Groital Company Ltd.

Background

Groital Company Ltd., established in 2014 in Akuapim South district of the Eastern Region of Ghana, specializes in the cultivation of fruits, mainly pineapple, and vegetables such as tomatoes and cucumber for the local and global markets.

[7] NPV is the total sum of the present value of expected future cash flows. Higher NPV values represent greater economic benefits. IRR is the discount rate for which the total present value of future cash flows equals the cost of investment. BCR is the ratio of the total benefit of a project relative to its costs; both benefits and costs are expressed in discounted present values.

As our suitability mapping suggested above, solar-powered irrigation is suitable in some areas of the Eastern Region. The region is considered less suitable for groundwater irrigation than for surface water; nevertheless, Groital depends on groundwater. Solar intensity in the region is in the range 3.1–5.8 kWh/m^2/day (Energy Commission 2012). Akuapim South district lies within the semi-equatorial climatic region, and experiences two rainfall seasons per year. The first lasts from May to June with the heaviest rainfall occurring in June; and the second runs from September to October. The total annual rainfall here averages 125–200 cm (GSS 2014).

Groital initially started its operations on a 0.8 ha area leased for 3 years. Currently, the business operates on a total area of 12 ha leased for 15 years. At the time the farm was established, it purchased irrigation water weekly from other farmers in the surrounding area who had hand-dug shallow wells. In 2015–2016, the area experienced water shortages during the dry season, which continued for over three months. The local drought reduced the availability of shallow groundwater. So, to mitigate the risk of crop failure and reduce the cost of purchasing water, Groital drilled a 110 m borehole and installed a solar pump.

Before deciding to invest in a solar pump and grow high-value crops, Groital conducted technical and market research, which suggested that there was a ready market for pineapple both locally and globally, yielding good profit margins. However, pineapple requires about 16 months to grow and harvest; so Groital decided to cultivate vegetables to generate income to meet operational expenses. The vegetables are grown in two 30 m x 80 m greenhouses (about 0.4 ha); currently 8 ha are allocated to the cultivation of pineapples.

Table 6 summarizes the basic data on the Groital business case.

Table 6. Business case 1: Direct funding to farmer.

Business case name	Groital Company Ltd.
Location	Nsakye, Eastern Region of Ghana
Value proposition	Pineapple of standard quality for export; vegetables for local markets
Organization type	Private (with partial funding from a donor – GIZ)
Objective	Profit maximization
Status of organization	Operational since 2014
Size of business	Medium (12 ha of land)
Major partner	GIZ
Technical and financial data	
Total land area (ha)	12
Total area under cultivation (ha)	8.4
Solar panel capacity	Eight 250 w polycrystalline solar panels, with a capacity of 1,000 W/m^2 each
Maximum flow rate (m^3/hr)	4.7
Source of water	Groundwater (depth 110 m)
Water storage capacity	22 m^3
Water distribution system	Sprinklers and drip
Economic viability indicators	
Capital investment (solar pump, borehole, sprinklers)	USD 30,855[a]
Annual turnover	USD 40,000
Farm gross margin (percentage of sales)	43
NPV	USD 57,134
Payback period (years)	3
Benefit-cost ratio (BCR)	3.17
IRR (%)	58

Note: [a] USD 1 = GHS 4.4 in 2016.

The Technology

The solar pump is a LORENTZ submersible pump with a rated capacity of 1,800 W and a daily output of 20 m^3 at a flow rate of 4.7 m^3/h. The system (solar pump, solar panels and accessories) was purchased from and installed by Pumptech Ltd. GIZ partially financed the installation costs under the EnDev program. Representatives from GIZ made quarterly visits to the Groital farm to inspect the system and assess the performance of the business.

The system lifts water from the borehole and transfers it to four tanks with capacities between 2 m^3 and 10 m^3 located at various points on the farm (Figure 6). The distance between the solar pump and the farthest tank is about 400 m. The total on-farm storage is 22 m^3. The pump is powered by eight 250 W polycrystalline solar panels, each with a rated capacity of 1 kW/m^2. The pump is manually controlled with a switch. The solar panels are mounted on a galvanized metal support structure covering a surface area of about 8 m^2. Water is applied to the crop through sprinklers and a drip system. A petrol pump is sometimes used to supplement power for water lifting, especially when more sprinklers (between 20 and 30) are used and when solar radiation is low (e.g., during cloud cover or for irrigating in the morning or late at night). During the dry season, the petrol pump is used to irrigate a quarter of the land under pineapple cultivation.

Pumptech periodically provides technical assistance to the farm, but Groital also contracts a private technician to service the system. No major repairs have been required since installation. Operation of the system is simple: Every team member of Groital, including laborers (comprising five permanent staff and 12 seasonal workers), can operate and maintain the system. This consists of regularly cleaning the solar panels, switching the pump on and off, opening the valves to fill the storage tanks, and conveying water to the crops. The solar pump system is not fenced; theft or vandalism in the area appears to be low risk.

The Groital Business Case

Groital is a privately-owned business driven by profit maximization in an environmentally and socially responsible manner, with a strong emphasis on delivering quality produce to customers. The farm uses improved seeds in the production of both pineapples (which are classified as first grade) and vegetables. The farm sells its pineapples to the Swiss company Hans Peter Werder AG (HPW), which supplies value-added agricultural products such as dried fruits to consumers in Switzerland and other parts of Europe. Groital signed an offtake contract making HPW its main client. As part of the offtake contract, HPW provides extension services to ensure that the pineapples produced by Groital meet its quality standards. On the other hand, the vegetables produced by the farm are sold to local supermarkets such as Shoprite and Eden Tree, and in open markets.

As part of its corporate social responsibility objective, Groital also supplies water for drinking and farm use at no cost to the inhabitants of the area. The company has built a 5,000-liter water tank at the nearest settlement, which is about 500 m from the borehole. The water is managed by Groital staff; someone is always posted at the storage tank. Groital is responsible for ensuring the availability of water, functioning of the pipes and for solving any technical issues. If there is a problem with the water supply or any pipe dysfunction, Groital manages the repairs. The tank is refilled every second day depending on the consumption, which varies seasonally: water use declines during the rainy season while about 100 people use the water during the dry season.

Local Value Chain

The Groital value chain is depicted in Figure 7. The company's customer segments vary by the type of produce. It supplies its fruit to HPW, which subsequently processes the fruit into value-added products for export. The vegetables are supplied to local open markets and supermarkets. GIZ and Pumptech Ltd. are partners through partial repayment for the cost of installation and technical assistance, respectively.

Figure 6. Solar panel (left) and storage tank (right) at the Groital farm, Akuapim South district, Eastern Region, Ghana (*photo:* Theophilus T. Kodua, 2017).

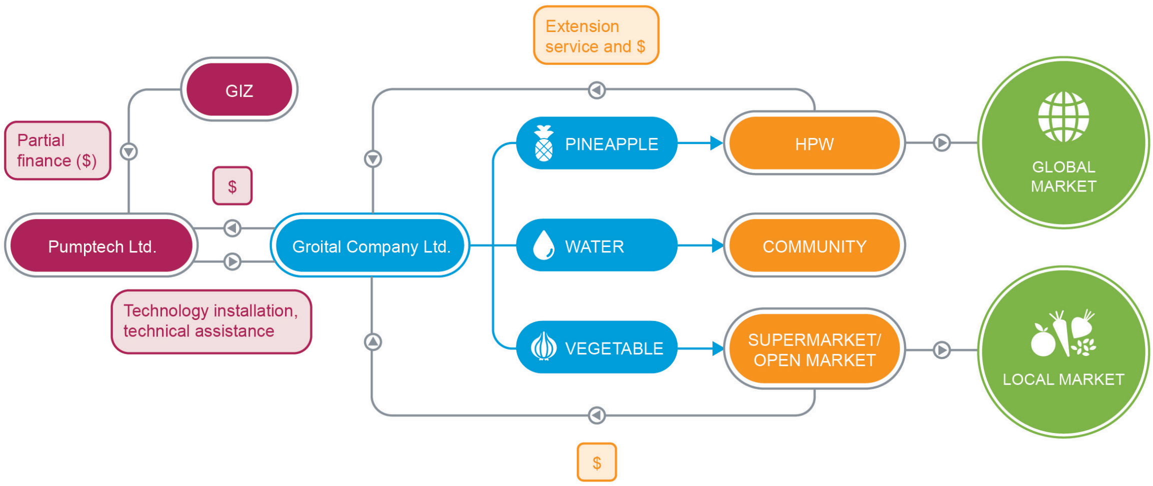

Figure 7. Groital Company Ltd. value chain.

Financial Analysis

The funding structure of Groital's initial investment in solar PV technology was as follows: 40% of the total capital cost came from GIZ, 30% from the owner's equity, and the remaining 30% from a cash prize Groital won in a startup competition funded by the flagship entrepreneurship support program of Total Petroleum Ghana Ltd. Details of the investment costs, including the solar pump, solar panels, support structure, delivery pipes, sprinklers, drips, other accessories and installation, are presented in Table 7. The total cost was USD 30,855—or USD 3,673 per ha—not including the cost of the community supply system. The solar PV system itself (solar pump, solar panels, installation accessories and charges) accounted for 22% of the total investment cost; the balance 78% was for the borehole, tanks, pipes, etc. Replacement of accessories, such as valves to control water flow, is done every 2 years.

Input Cost and Value of Output

Data from the 2015/2016 production year were collected on the quantities and costs of inputs used in production, and the quantities and values of outputs. A monetary value for the total output was calculated using the quantities and corresponding prices of different outputs. The inputs considered in this analysis included the costs of land leasing, land preparation, seeds, fertilizer, pesticides and labor. Other costs included the running cost of the petrol pump, the tools (e.g., protective gear) used in operating the farm, and the transportation cost for delivering farm output to the market (Table 8).

Notably, labor accounts for the largest share of input costs (on average, 65% of the total), followed by the cost of seeds (14%). According to Groital, the number of irrigation events requiring the use of the petrol pump during the dry season is, on average, 20 times per month, at a cost of USD 11.36 per ha per irrigation event and a monthly fuel expense of USD 5. Therefore, the operational cost of using the petrol pump is USD 1,818/ season (USD 909/ha).

Financial Feasibility of the Business Case

The total investment cost, farm input costs, total value of outputs and the resulting financial returns of the Groital business case are presented in Table 9. Since no major repairs of the system had taken place since installation, O&M costs of the solar PV technology were assumed to be 3% of the investment cost, based on Groital's estimates. The O&M cost of the petrol pump was assumed to be 6% of its investment cost. The expected life of the solar PV system was estimated by the manufacturers to be 15 years. The total value of the produce and farm input costs were determined based on the average price, yield and input costs. A discount rate of 13% was assumed based on the minimum base rate of the Bank of Ghana,[8] adjusted for inflation.

[8] The average base rate of the Bank of Ghana in 2017 was 25.7% and the annual inflation rate was 12.4% (https://www.bog.gov.gh/).

Table 7. Capital cost of a 1.8 kW solar PV system and other investment costs of Groital Company Ltd.

Item	Cost (USD)[a]
Solar PV system	
LORENTZ solar pump (capacity 1.8 kW)	2,795
PV panel and support structure (250 W polycrystalline)	2,812
Installation charges	327
Installation accessories	967
Total cost of solar PV system	*6,901*
Cost of land for borehole construction	3,636
Borehole construction	1,818
Cost of greenhouse infrastructure	5,727
Storage tanks	2,364
Delivery pipes, sprinklers and drips	6,818
Petrol pump	182
Other costs (valves to control flow of water)	3,409
Total investment cost	30,855

Note: [a] USD 1 = GHS 4.4 in 2016.

Table 8. Input and output variables of Groital Company Ltd.

Variable	Value
Total land size (ha)	12
Land under pineapple cultivation (ha)	8
Land under vegetable cultivation (ha)	0.4
Yield (kg/ha/season)	
Pineapple	30,000
Vegetables	12,500
Value of output (USD/kg)	
Pineapple	0.15
Vegetables	0.91
Input costs (USD/ha/season)	
Land leasing (USD/ha/year)	142
Land preparation	78.41
Seeds	195.45
Fertilizer (organic and inorganic)	90.91
Pesticides	121.59
Labor – seasonal	263.07
Labor – permanent	635.80
Other costs (USD/season)	
Cost of using petrol pump	1,818
Delivery of produce (transportation cost)	2,866
Tools (protective gear, replaced annually)	917

Table 9. Cost-benefit analysis of Groital Company's solar PV system.

	Value
Investment cost (USD)	
Investment cost of solar PV system and other costs	30,673
Investment cost of petrol pump	182
Total investment cost (USD)	*30,855*
Sales revenue (USD/year)	
Total sales from pineapple and vegetables	40,000
Farm input and other costs (USD/year)	
Annual land leasing	1,648
Land preparation	627
Seeds	3,409
Fertilizer	764
Labor	9,585
Pesticide	973
Cost of using petrol pump	1,847
Delivery of produce (transportation cost)	2,866
Tools (protective gear)	917
Total cost (USD/year)	*22,636*
Gross margin (USD/year)	*17,364*
O&M cost (USD/year)	218
Net farm income (USD/year)	17,146
NPV (USD)	76,289
Payback period (years)	3
IRR (%)	58
Benefit-cost ratio (BCR)	3.80

The analysis shows an average gross margin of 43% and a net farm income, after accounting for O&M costs, of USD 17,146. At a discount rate of 13% and expected life of 15 years, the business case resulted in a positive NPV of USD 76,289 and BCR of 3.80, indicating that the business is financially viable. The farm income is sufficient to recoup the investment cost of the solar PV system, including other costs such as the borehole and water distribution system. The analysis also shows that even if a petrol pump was used as a complementary energy solution to the solar pump, the business would still be profitable.

The results indicate that the farm income is high enough to recover the total investment cost of the system, including the donor subsidy. The implication is that with access to finance such as bank loans, this business model is financially feasible *without* funding from donors. However, for the interim period, donor support is needed because financial service providers in Ghana generally do not provide credit for irrigation and related technologies. Banks are not familiar with the irrigation sector and lending requirements, and solar PV technology is relatively new. This points to the need for innovative financing or leasing mechanisms to enable small and medium farms to have access to the technology (Merrey and Lefore 2018a).

This analysis did not compare the farm's present performance with how it had been doing before the solar PV system was installed, when it was purchasing irrigation water from neighboring farmers. This is because the farm is operating a larger area (12 ha) with the solar PV system compared to 0.8 ha earlier. When the farm decided to expand, the whole business model changed. Buying irrigation water from other smallholder farmers' hand-dug wells was not feasible over the larger area. So, it decided to drill its own borehole and equip it with a solar PV system.

This business case is not a small-scale enterprise in the Ghanaian context; the Groital farm is larger than the average 2 ha farm. However, the case does illustrate how smallholder farmers with access to relatively larger areas of land can expand to medium-sized farms and profitably utilize solar and other irrigation technologies. Further, it provides an example of how donor seed money can enable a farmer to transition to a commercial agribusiness. As a business model, this could be replicated or scaled up on farms with land sizes ranging from 2 ha to 10 ha. At the same time, this business model requires strong farm and business management skills coupled with good market linkages (e.g., secure offtake contracts) for farm produce. These requirements are not universally available as yet in rural Ghana. Scaling Groital's business case not only requires access to finance or a bigger land size but also to management skills and secure market linkages. However, donor- or government-funded technology provisions for smallholder farmers more often than not focus more on improving farm production and less on developing a business plan that looks at the whole value chain in tandem with improving farmers' management skills and securing a market for their produce.

Business Case 2: Cooperative Model—the Case of the Datoyili Cooperative

Background

Northern Ghana is characterized by a unimodal rainfall regime. Rain-fed agriculture is feasible here for 4 to 5 months; the remaining 7 to 8 months are dry. Farmers usually grow staple foods such as millets, sorghum, maize and rice in the rainy season and vegetables in the dry season, if they have access to water and other inputs. For such irrigating households, vegetable production can make an important contribution to their overall income through sales to both local and external markets. Most of these farmers carry out simple hand-watering with cans, which is time consuming and limits the area that can be cultivated. Some farmers use small diesel or petrol motor pumps to expand the area under cultivation, but this opportunity is restricted to farmers who can afford the initial investment and O&M costs.

NewEnergy is a Ghanaian NGO based in Tamale, capital of the Northern Region. In 2014, NewEnergy designed and developed solar-powered irrigation schemes for four farmer associations at Tamalgu in Karaga district, Nakpanduri in Bunkpurugu-Yunyoo district, and Datoyili and Fooshegu in the Tamale Metropolitan Area. With funding from UNDP under the SEforALL initiative, the project installed one solar irrigation pump in each of these four communities to irrigate a total area of 15 ha. The goal of the project was to make sustainable energy accessible to smallholder farmers for productive uses. This analysis examines the Datoyili Cooperative and Marketing Society business case. The solar irrigation system was developed on a build-operate-transfer basis: NewEnergy was to control the technical aspects of equipment maintenance for 2 years, after which the cooperative would take over O&M as well as tariff setting and revenue collection functions.

Prior to the solar irrigation system, individual Datoyili farmers had been using petrol and diesel pumps to abstract water from the Kulobon stream, which collects drainage water from a formal irrigation scheme. However, rising fuel costs made the use of these pumps unviable, forcing some of the farmers to migrate out of the area. The NewEnergy project established a cooperative of 12 farmers to cultivate a total area of 2 ha during the dry season, with each farmer cultivating his or her own small plot. In addition, the farmers kept their separate, individual farm plots. Of the 12 farmers, seven also get access to irrigation water from the scheme for their individual farms, taking advantage of the proximity of their farm plots to the solar irrigation system. The remaining five farmers continue to use their petrol and diesel pumps to irrigate their individual farms.

Table 10 summarizes the basic data of the Datoyili business case.

The Technology

NewEnergy installed a LORENTZ PS 4000 pump with a solar panel capacity of 3,500 W mounted on a galvanized metal support structure. The system is a direct current system (without inverters and batteries). When installed in 2014, it had an expected life of 15 years. It was designed to draw about 120–160 m^3 of water per day under low head and pressure conditions for storage and irrigation. The system has a storage tank with a total capacity of 8 m^3. Water distribution to fields and crops is via furrows and drip irrigation.

The Datoyili Cooperative Business Case

This business case involves joint ownership of a solar PV irrigation system by 12 farmers for dry-season vegetable farming. Although NewEnergy installed the system on a build-operate-transfer basis, it continued to be involved in its management. The 12 members of the cooperative cultivated about 2 ha of land during the dry season under a cost and benefit sharing model. NewEnergy, together with the cooperative, instituted tariffs based on rates found in other formal, public irrigation schemes.[9] The NGO had an exit strategy to put the cooperative fully in charge of O&M, tariff setting and revenue collection. Unfortunately, in 2017, 11 solar panels were stolen. This resulted in the failure of the system and cancellation of the project.

Management and Institutional Structures

The Datoyili Cooperative has a chairman, a secretary and a treasurer; an elderly member of the community was selected as a non-member patron to help with conflict management. The cooperative members operated the system and carried out basic technical maintenance such as cleaning panels. In the event of any major technical challenge, NewEnergy was required to intervene or call

[9] It is not clear why the tariffs were not based on the actual O&M costs of the Datoyili system.

Table 10. Business case 2: Datoyili cooperative model.

Business case name	Datoyili Cooperative
Location	Datoyili, Northern Region, Ghana
Value proposition	Reliable access to irrigation water at a low cost for dry-season vegetable farming
Organization type	Cooperative
Status of organization	Operational 2014-2016; not operating since 2017 due to theft of solar panels
Number of farmers (members of cooperative)	12
Scale of business	Small
Major partners	NewEnergy, UNDP, Energy Commission, Pumptech Ltd.
Technical and financial data	
Total area under cultivation (ha)	2
Maximum flow rate (m^3/hr)	5-7
Source of water	Surface water (stream)
Water storage capacity (m^3)	8
Water distribution system	Furrow, sprinkler and drip
Economic viability indicators	
Capital investment (solar PV system, storage tanks, water distribution systems) (USD)	17,910[a]
Farm gross margin (%)	80
NPV (USD)	-184
Payback period (years)	7
Benefit-cost Ratio (BCR)	0.99
IRR (%)	12.80

Note: [a] USD 1 = GHS 4.4 in 2016.

upon Pumptech Ltd. for assistance. However, no major operational challenges arose. Pumptech Ltd. addressed changing seals on the solar pump at no cost under the warranty agreement.

Since the cooperative was registered, farmers were required to follow the guidelines outlined by the Department of Cooperatives.[10] NewEnergy supported the group during the registration process, taking the members through a six-month capacity development and training program prior to formal establishment of the cooperative. They were trained on organizing meetings, electing leaders, setting levies, resolving conflicts and keeping records. As per the plan, NewEnergy was to gradually exit from O&M of the system, and the cooperative was expected to implement sustainable tariff setting and revenue collection systems, and refine operational procedures as well as establish an O&M fund.

The cooperative was required to recover from its members a total annual tariff of about USD 114 (GHS 500) at the rate of about USD 57/ha. These funds would go to an account managed by the cooperative for O&M expenses. Members paid a share based on the size of the plot irrigated. This rate was based on prevailing tariffs at public irrigation schemes rather than on site-specific costs. Upstream of the irrigation scheme, farmers pay between USD 56 and USD 67 per ha per season, depending on the proximity of their land to the irrigation system.

The cooperative set its own rules and regulations regarding water use and allocation. However, water allocation was a challenge. The available water was adequate for all the members, but the farmers did not develop an irrigation schedule for water sharing. NewEnergy noted the main challenges as follows:

- Lack of cooperation among farmers in scheduling irrigation; farmers draw water at the same time.
- Failure to match water demand to supply from the solar-powered irrigation system (for example, farmers try to irrigate before sunrise).

[10] The Department of Cooperatives provided training to the group on the principles of cooperatives, meetings, conflict resolution, networking and financial management. Training and capacity building of the group was a precondition for registering the group. Registration as a cooperative requires a small registration fee of GHS 250 (USD 58) and is not perceived as being difficult for farmers to pay.

- Exposure to technology theft. To mitigate this, the system was removed each year after the dry season and reinstalled at the beginning of the next dry season.

However, this theft mitigation measure was not sufficient; as noted above, 11 panels were stolen in 2017, resulting in cancellation of the project at this site. NewEnergy suggested that one of the reasons for the theft was the location of the farm close to a main road.

Local Value Chain

The solar-powered irrigation system was operated and managed by Datoyili Cooperative with NewEnergy and Pumptech Ltd. as key partners in installing the technology and providing training and technical assistance (Figure 8). Agricultural inputs such as seeds, fertilizer and agrochemicals were procured from the nearby market in Tamale. Produce was sold to bulk buyers at the farm gate.

Financial Analysis

UNDP fully financed the solar-powered irrigation system through the Energy Commission to the project implementer, NewEnergy. The financial viability of the system was assessed in terms of NPV, BCR and IRR. Further analyses were conducted to compare the economic performance of the solar PV system to an alternative, a diesel-powered system. A sensitivity analysis was also carried out.

The total capital cost of the solar pump irrigation system and other costs amounted to USD 17,910 (Table 11). This included the cost of the solar pump, solar panels, panel support structure, installation accessories, transportation and installation, water delivery pipes and storage tank. The investment cost of the solar PV system was USD 8,955/ha.[11] NewEnergy estimated that the pump had the capacity to irrigate 5 ha. However, after installation, it was realized that the stream did not have sufficient water to allow more farmers to use it (see section *Sensitivity Analysis*).

Input Costs and Value of Output

The farm input and output data relating to the Datoyili Cooperative are presented in Table 12. The total output is the sum of the yield of vegetables multiplied by the average prices, which were collected from Datoyili Cooperative's selling experiences over the dry season of 2015/2016. The input costs include the monetary values of land preparation costs, seeds, fertilizer, pesticides and labor. Among the five inputs, fertilizer accounted for the largest share, on average one-third, of the total input cost. This was followed by seeds and labor, each accounting for 20% of the total input cost.

Financial Viability of the Business Case

Table 13 presents the total investment cost, total value of the produce, farm input cost and the resulting value of farm performance indicators. The expected life of the system was 15 years. O&M costs were included and a discount rate of 13% was assumed based on the minimum base rate of the Bank of Ghana, adjusted for inflation.

The business case resulted in a positive average gross margin of USD 2,853 per year and a net farm income, after accounting for O&M costs, of USD 2,739 per year. However, considering the discount rate of 13% and expected life of 15 years, the business case resulted in a negative mean NPV of USD 185 and a BCR of 0.99. This indicates that the farm income, although positive, was not high enough to recover the initial investment cost of the system.

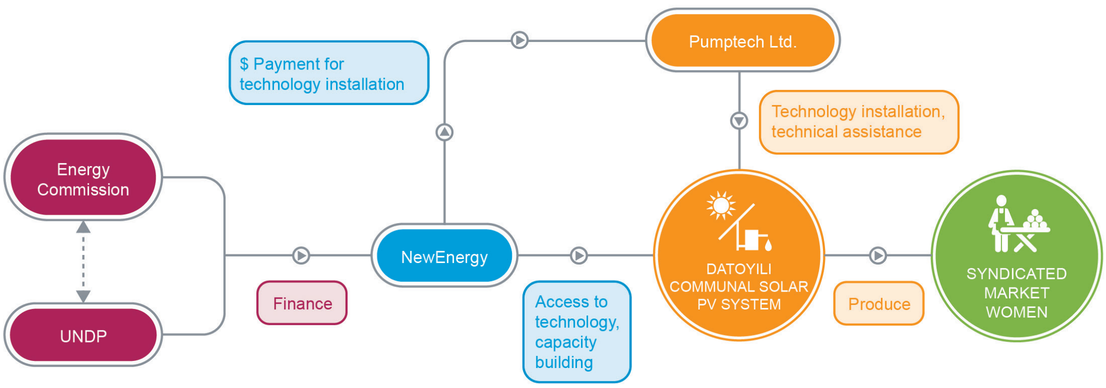

Figure 8. The Datoyili Cooperative value chain.

[11] This contrasts with the USD 3,673/ha investment cost of the Groital Company Ltd. farm.

Table 11. Capital cost of the solar PV system and other costs at Datoyili Cooperative.

Item	Cost (USD)
Solar pump system	
LORENTZ solar pump	5,879
Photovoltaic panel and support structure	5,909
Transportation and installation	1,809
Installation accessories	1,447
Total cost of solar PV system	*15,044*
Storage tank and stand (8 m³)	1,024
Water delivery pipes	152
Drip irrigation kit	1,280
Sprinklers	410
Total investment cost	17,910

Table 12. Farm input and output data for the Datoyili Cooperative.

Description	Unit	Value
Land size	Ha	2
Output		
Value of vegetables sold	USD/ha	1,791.5
Input costs		
Land preparation	USD/ha	43.91
Seeds	USD/ha	73.04
Fertilizer	USD/ha	115.36
Pesticides	USD/ha	64.62
Labor	USD/ha	68.26
Total input costs	USD/ha	365.19

The economic performance of the solar PV system was then compared with that of a diesel-powered irrigation system with the same pump size of 3.5 kW. The capital and operational costs of the diesel system were based on primary data collected from NewEnergy, complemented by secondary data. It was assumed that the water distribution system (sprinklers and drip), value of the vegetables and other input costs were the same for the two systems.

Table 14 compares the costs and benefits of the solar PV and diesel irrigation systems. The total investment cost of the diesel system was USD 5,248. The solar PV system required a significantly higher initial investment, about three times the cost of the diesel system. However, the O&M costs of the diesel system were higher than for the solar PV system.

The difference in the performance of the two systems was not significant: both systems resulted in a negative NPV. However, the solar PV system gave a higher net farm income over its useful life compared to the diesel system. The annual costs of running a diesel pump were significantly higher than those for a solar PV pump. The payback period for both systems was 7 to 8 years.

Table 13. Cost-benefit analysis of Datoyili Cooperative.

Item	Value
Total investment cost (USD)	17,910
Benefit (USD/year)	
Value of vegetables produced	3,583
Farm input and other costs (USD/year)	
Land preparation	88
Seeds	146
Fertilizer	231
Labor	137
Pesticide	128
Total farm input cost	*730*
Gross margin (USD/year)	*2,853*
O&M costs (USD/year)	114
Net farm income (USD/year)	2,739
NPV (USD)	(185)
Payback period (years)	7
BCR	0.99
IRR (%)	12.8

Table 14. Cost-benefit analysis of solar PV and diesel-powered irrigation systems.

Item	Solar PV system	Diesel system[a]
Investment costs (USD)		
Pump	5,872	3,409
Photovoltaic panel and support structure	5,902	
Transportation and installation cost	1,807	
Installation accessories	1,445	
Storage tank and stand (8,000 liters)	1,023	
Water delivery pipes	152	152
Drip irrigation	1,278	1,278
Sprinklers	409	409
Total investment cost	17,910	5,248
Benefit (USD/year)		
Value of vegetables produced	3,583	3,583
Total farm input cost	730	730
Cost of diesel		1,836
Gross margin (USD/year)	*2,853*	*1,017*
O&M costs (USD/year)	114	205
Net farm income (USD/year)	2,739	812
NPV (USD)	-184	-88
Payback period (years)	7	8
BCR	0.99	0.99
IRR (%)	12.80	12.90

Note: [a] Based on field data collected from Datoyili Cooperative and Priesemann 2014.

Sensitivity Analysis

Based on NewEnergy's estimate, the solar PV pump has the capacity to irrigate 5 ha of land. However, after installation of the system, it was realized that the stream from which farmers source water did not have sufficient water to allow more farmers to use it. If the full 5 ha had been irrigated, the investment cost per hectare would have been USD 3,578, similar to the Groital business case. To assess the sensitivity of the economic performance of the solar PV system to variation in land size, an analysis was conducted assuming that 5 ha were irrigated as planned. In this sensitivity analysis, the effect of the increased land size only affects the variable farm input costs and revenues.

Table 15 shows the costs and benefits of the solar PV system irrigating 5 ha. The analysis demonstrates that the system results in a positive NPV of USD 24,288 and a BCR of 2.53 with a shorter payback period of 3 years. Thus, if the system had been able to irrigate the full 5 ha, it would have been viable. This emphasizes the importance of implementing a proper assessment of the water supply to avoid underutilization of the system after installation.[12]

The high initial investment cost limits the adoption of solar PV technology for smallholder farmers. Therefore, the promotion of this technology in Ghana relies on donor subsidies and government-funded investments, although subsidies have limited potential to reach a large number of smallholder farmers, and do not necessarily result in successful implementation of the technology, as evidenced by the Datoyili case study. The fact that the technology was fully funded by a donor might have had a bearing on the design and implementation of a system that did not fully meet water availability, thus influencing system performance. This possibility needs further investigation when designing suitable financing schemes for solar PV technology for smallholder farmers.

For solar PV technology to be successful for smallholder farmer cooperatives, a number of conditions must be met. The key lessons learned from the Datoyili Cooperative include the following:

- An accurate assessment of the water supply is critical: If the system had been able to irrigate the full 5 ha, it would most likely have been viable (or a scheme designed for 2 ha might have cost significantly less).
- Proper management of the system is necessary with clear rules and regulations on water use and allocation.
- Established market links to sell farm produce are critical.
- Proper mitigating measures are needed to minimize the risk of technology theft, including designing suitable insurance products to safeguard against technology theft and other damages.
- Capital costs need to be reduced significantly (or favorable financing made available).

Table 15. Cost-benefit analysis of the Datoyili solar PV system assuming cultivation of 5 ha.

Item	Value
Total investment cost (USD)	17,910
Total value of vegetables produced (USD/year)	8,958
Total farm input cost (USD/year)	1,826
Gross margin (USD/year)	7,132
Net farm income (USD/year)	7,018
NPV (USD)	24,288
Payback period (years)	3
BCR	2.53
IRR (%)	39

[12] Additional analysis of the 2 ha scenario showed that a reduction of 2% in the investment cost (assuming all other variables stayed the same) would bring the NPV to zero and the BCR to one. Similarly, an increase in the value of produce by 3% (assuming all other variables stayed the same) would bring the NPV to zero, i.e., not negative. This suggests that, in principle, even the 2 ha scenario could breakeven through a combination of cost reduction and increased production.

Business Model Scenarios for Upscaling Solar Photovoltaic Irrigation in Ghana

Business models can unlock the value embedded in new or existing technologies and convert it into market outcomes. This section presents three business model scenarios for providing smallholder farmers in Ghana with access to solar PV irrigation. These models are designed based on insights gained from empirical cases as well as an analysis of the policy and regulatory framework, the technology supply chain and environmental suitability.

The key value proposition of solar PV technology for irrigation is the provision of reliable access to irrigation water at a low cost for dry-season farming.[13] With this key value proposition in mind, we present the following business models:

- *Business model 1:* Individual ownership with multiple use water services (MUS)
- *Business model 2:* A cost-sharing model (communal ownership by a group of farmers)
- *Business model 3:* Solar irrigation service provider model

Under the individual and shared ownership models, several alternative financing scenarios are considered, including: (i) matching grants or partial capital subsidy from public or donor agencies; (ii) revolving fund financing; and (iii) trade credits such as a rent-to-own scheme.

Business Model 1: Individual Ownership with Multiple Use Water Services (MUS)

Solar PV irrigation provides small-scale farmers with an opportunity to improve farm productivity and profitability. The technology has proven to be technically and financially viable with an attractive return on investment depending on, among other factors, the size and location of the farm and the crops grown. However, the high initial investment cost and the lack of suitable financing schemes are big challenges. Besides, on small farms, water demand may in fact be insufficient to justify investing in high-cost irrigation technologies. Depending on the crop, soil type and climate conditions, irrigation is seldom practiced on a daily basis, and the pump may only be used for a limited time each year. Some estimate the utilization factor at only 15%, implying that the solar PV system lies idle for most of the year (Shakthi Foundation and KPMG 2014). Developing ways to use the technology during the off days can significantly improve economic performance. Thus, business model 1, individual ownership, would make more economic sense if it is a multiple use water services (MUS) model.[14]

In this business model, a farmer purchases a solar PV pump to irrigate his/her own farm, meet other needs such as water for livestock, home gardening and domestic use, and sells water to neighbors. If several farmers in the area also purchase pumps, a water market may emerge. Groital Company Ltd. implements a variant of the MUS model. As part of its corporate social responsibility objective, it supplies water for different uses to inhabitants in the area at no cost, and has also installed a water storage tank, an additional investment; one could envision charging a fee for this service. Moreover, demand for water for agriculture is seasonal with peak demand during the dry season and lower demand during the rainy season. Thus, the potential additional income from selling water needs to be assessed against meeting the farmer's own needs plus the additional cost of water storage and delivery facilities.

Despite the economic benefits of solar PV technology for irrigation, the high initial investment cost may still limit its adoption, especially by smallholder farmers. Promotion of the technology in Ghana, therefore, currently relies on donor subsidies and/or government-funded investments, although subsidies have only a limited potential to reach a large number of smallholder farmers.

Figure 9 depicts the value chain for the MUS model. For this business model, alternative financing schemes for the initial capital investment need to be explored. The fully subsidized model could be adapted to include a risk-sharing mechanism through: (i) an equity-cum-subsidy model; (ii) a revolving fund approach; and (iii) trade credits.

[13] A potentially important subsidiary value proposition is the provision of supplementary irrigation to other crops when there are delays in rainfall during the main growing season. However, we do not have the data to analyze this.

[14] An alternative that needs further research is using the solar panels to provide energy for other uses, such as running other farm equipment, providing domestic electricity, and recharging batteries.

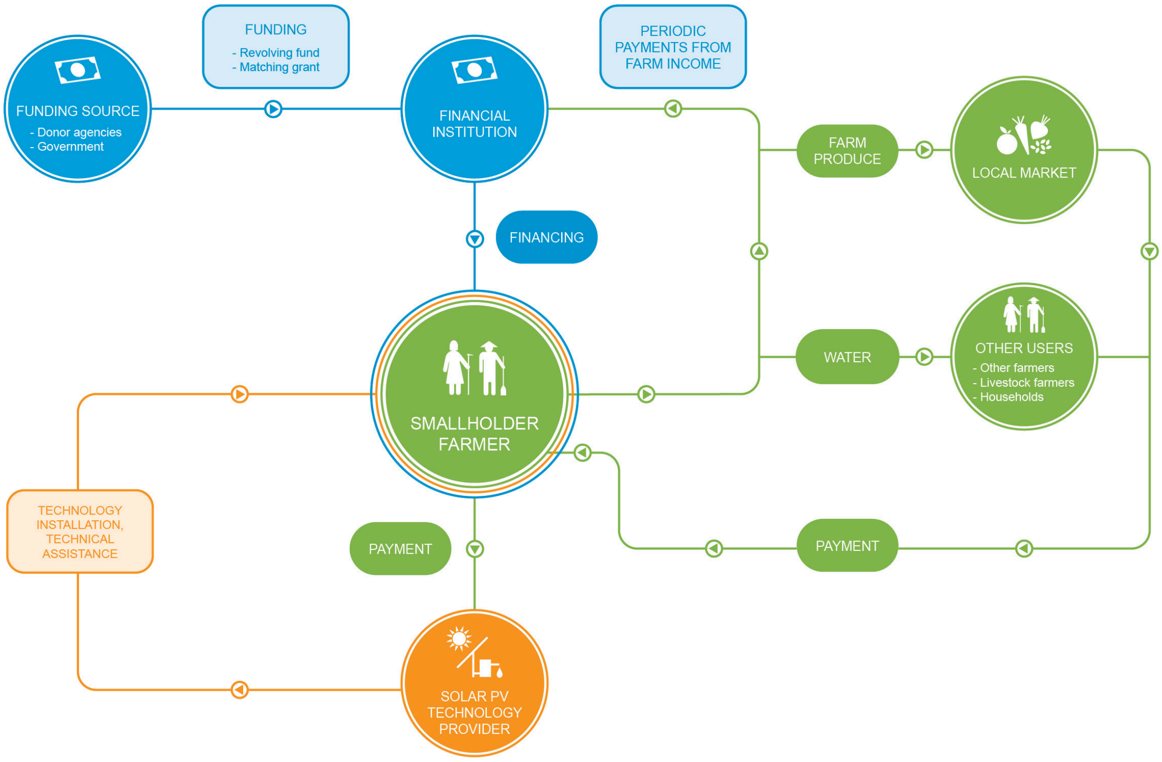

Figure 9. Value chain for individual ownership with the MUS model.

i. *Equity-cum-subsidy model.* In this model, the technology supplier provides farmers with solar PV technology at the normal market price, a share of which is borne by the government/donor as a subsidy; the remainder is paid by the farmer. This model could benefit from the existing agricultural financing initiatives available in Ghana. For example, the Northern Rural Growth Programme (NRGP), funded by the African Development Bank and the International Fund for Agricultural Development (IFAD), has introduced a subsidy scheme through matching grants under which farmers can purchase equipment such as irrigation pumps. The Financing Ghanaian Agricultural Project (FinGAP), supported by USAID, has assisted financial institutions and business advisory service providers to facilitate private finance and invest in selected crop value chains. This includes a 'pay-for-results' approach to financing institutions to incentivize, i.e., subsidize loans to enable smallholders to purchase equipment. Many smallholder farmers may still be unable to cover part of the investment cost, particularly due to limited access to long-term finance. This can be partly overcome through in-kind contribution by farmers toward the initial investment. Our analysis of the technology supply chain revealed that although the existing solar PV technologies installed at smallholder farms have mostly been funded by donors, farmers contributed about 50-60% of the investment in kind or in cash. The in-kind contribution is mostly labor, e.g., digging their own water source or storage and building basic fencing.

ii. *Revolving fund.* In this approach, a fund is established by a donor or public sector institution in partnership with local banks to offer low- or no-interest loans with favorable repayment terms to underserved smallholder farmers, including women. Under this scheme, loans are provided to cover the initial investment costs of a solar PV pump. A portion of the resulting farm income is then used to repay the loan into the revolving fund until the original investment is recovered. The repayments into the fund are then utilized to finance other farmers, thereby allowing the capital to revolve and potentially create a sustainable financing mechanism.

iii. *Trade credit.* Another financing option is trade credits provided by the suppliers of technology. Currently, the major suppliers of solar PV technology (such as Pumptech) do not have a credit scheme targeted at small-scale farmers due to the high risk of default. Past attempts to offer farmers technology on credit have not worked well: credit was offered with payment to be made over an extended period of time, but most farmers defaulted. Pumptech is in discussion with rural banks to design alternative credit schemes for smallholder farmers, though they remain inconclusive. One option could be a *rent-to-own* scheme in which the suppliers provide technology on loan to farmers. The solar PV system is the collateral. Farmers pay a fixed periodic (e.g., monthly) fee and interest is charged on the declining principal balance. When the balance has been paid in full, the farmer gets to own the equipment. This financing model has shown positive results in other African countries (Merrey and Lefore 2018a).

Business Model 2: Cost-sharing Model

An alternative to individual ownership is the shared model, in which a group of farmers jointly owns a solar PV irrigation system. The rationale for joint ownership is based on the notion that group-based systems can facilitate access to finance to cover the initial capital investment, especially for poor smallholder farmers. The group members share costs and risks as well as the benefits. Joint investments allow smallholders to pool collateral and negotiate for a lower interest rate (Otoo et al. 2018). Such a system could also be used to provide other water services – an MUS model.

This model, however, works only when there is social cohesion among the group members. The sustainability of cost-sharing models depends greatly on choosing an appropriate management and governance model as well as on its profitability. Shared solar pump ownership allows farmers to increase usage of the system compared to the individual ownership model. However, the transaction costs of negotiating the joint investment as well as sharing the use of the system on an ongoing basis need to be carefully examined and traded off against the benefits of lower initial investment cost for the individual members.

Once it has been decided where to install the system, an agreement must be reached among the group members on how to share the use of the pump, its expenses and the responsibility for maintenance on an ongoing basis. Promoting joint ownership of solar pumps among small farmers requires more than a simple assessment of the opportunity to obtain finance for the initial investment. It is also critical to develop a cohesive group with clear rules on conflict resolution, financial management, water-sharing mechanisms, and membership (Merrey and Lefore 2018b).

Experiences with cost-sharing models in Ghana have been mixed. For example, the Datoyili Cooperative, our second case study, is no longer operational, while the other three cooperatives in the same program are still functioning. One factor leading to the failure of the Datoyili system was the lack of cooperation on irrigation scheduling and timing; theft of the equipment delivered the final blow.

Financing options such as a revolving fund and trade credits described in the individual ownership model above could also be applied to a cost-sharing model. Funds could be made available to farmer groups directly or through an implementing agency. Figure 10 depicts the value chain for a joint ownership model implemented through a third-party agency. The implementing agency installs the system on a build-operate-transfer basis. As in the case of NewEnergy, the implementing agency could be a local NGO with the appropriate mandate and expertise. Its roles would include obtaining finance, construction and initial operation of the system, collecting fees and building management capacities among farmers. A clear exit strategy would be essential, though the NGO may continue to provide periodic technical support.

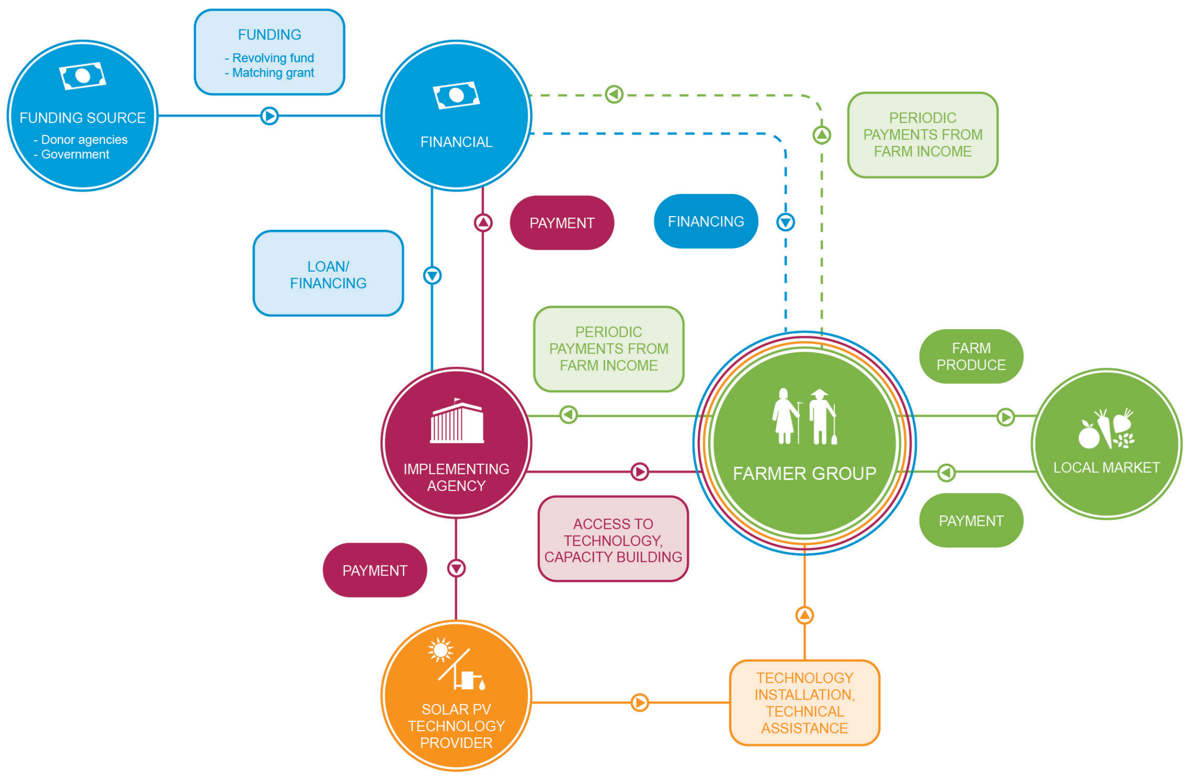

Figure 10. Value chain for a joint ownership model.

Business Model 3: Solar Irrigation Service Provider Model

The solar irrigation service provider model addresses the financing issue. In this model, the solar PV system is owned, operated and maintained by a supplier or third party. With the help of low-cost finance, partial grants and other fiscal incentives, entrepreneurs own and operate solar PV systems to provide irrigation water services to farmers for a fee. The fees from water sales are used to repay the loan. Merrey and Lefore (2018a) described several variants of this utility model implemented in Senegal, Morocco, Bangladesh and India. The service provider assumes the technical, operational and financial risks, and farmers purchase irrigation services on demand.

This business model might be attractive to smallholders as it avoids the high upfront costs as well as the need to manage, operate and maintain the system. Furthermore, instead of promoting individual ownership of solar pumps that may be underutilized, setting up young entrepreneurial farmers as Solar Irrigation Service Providers could help create a competitive water market by offering farmers an irrigation service at an affordable price (Shah et al. 2018). This model has been implemented for domestic water use at several sites in the Northern, Upper East, Ashanti and Greater Accra regions of Ghana. Pumptech has implemented this model for community water supply systems and believes that an irrigation service model has the potential to be viable. However, it has yet to test it on the ground. A possible variant of this would be a MUS model: providing water for domestic, irrigation, livestock and other purposes: iDE has installed five solar MUS systems in Nepal, and states that costs are recovered "in a couple of years."[15]

The reliability of such a service would be of fundamental importance to end users as it would allow them to make informed decisions, while the creation of demand for an irrigation service will be crucial to strengthen irrigation supply chains and services. However, there are several dimensions of water service delivery, including allocation, scheduling and delivery (FAO 2013). Ideally, the service will include not only delivery of a certain volume of water but also flexibility in terms of timing and volumes delivered to match water demand and supply. Figure 11 illustrates the value chain for this model.

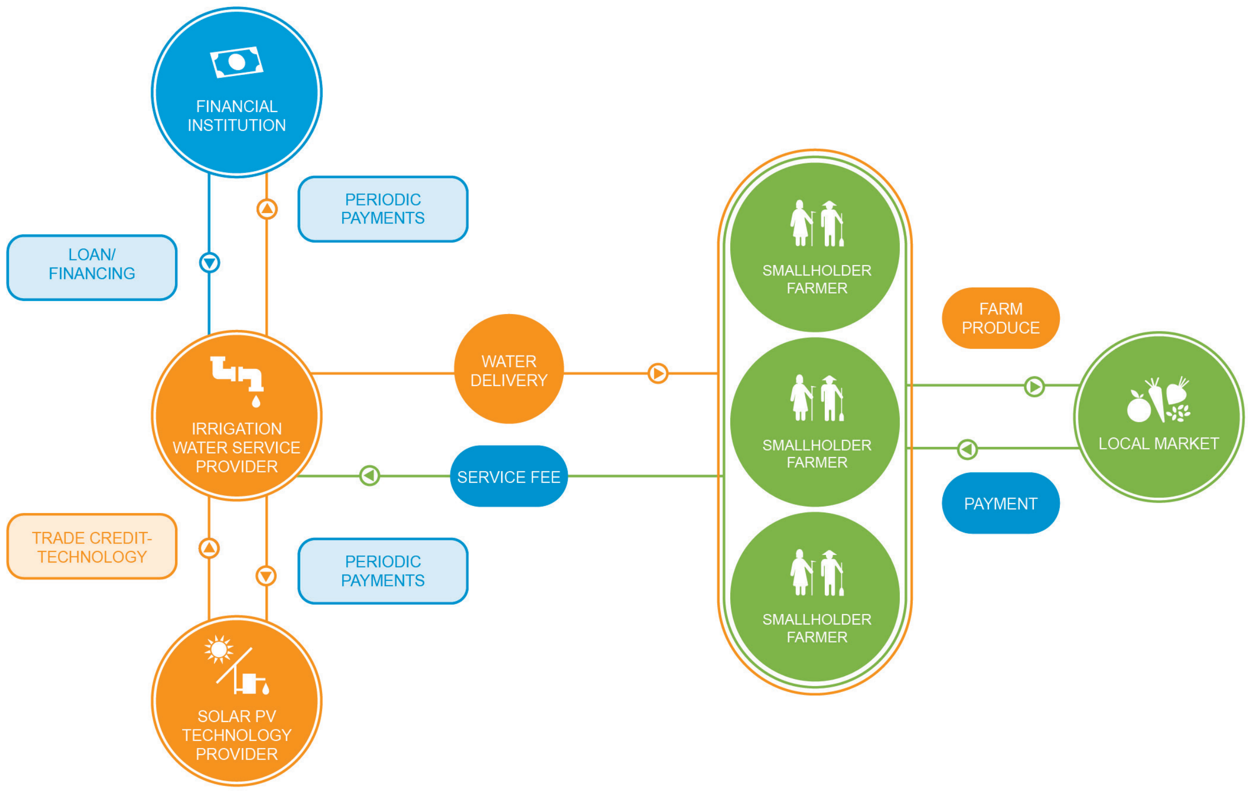

Figure 11. Value chain for the solar irrigation service provider model.

[15] https://www.ideglobal.org/key-project/multiple-use-water-systems-deliver-benefits (accessed on August 12, 2020).

This business model is based on the notion that professional irrigation water service providers can operate and maintain the systems more effectively than individual smallholder farmers, and the time the system is in operation would be far greater, especially if it is an MUS model. This would contribute to catalyzing competitive irrigation service markets and building assurance among financiers as well as technology suppliers. Financing options such as loans from financial institutions or trade credit from technology suppliers can also be considered under this model. Financial institutions can forge partnerships with service providers to finance the capital costs.

Conclusion: Potential of Solar Photovoltaic Irrigation Business Model Scenarios

This section has assessed three possible solar PV irrigation business models; they are not conclusive but indicative of the potential. To conclude, first, there are several potentially viable business models for scaling out the use of solar PV irrigation systems. Second, the return on solar PV irrigation investments can be enhanced by increasing the usage rate of the equipment, for example, by providing water for multiple purposes, and growing high-value crops requiring frequent irrigation. Third, high utilization of solar pumps works only in areas with good groundwater recharge rates or adequate surface water, as well as where there is a strong demand for irrigation service. When considering groundwater levels up to 25 m deep, our suitability mapping analysis revealed that there is a potential area of 2.3 Mha suitable for solar PV pumping in Ghana, with the Northern Region having the largest potentially suitable area. However, a thorough analysis of groundwater recharge rates should precede implementation of these business models at scale (see section *Environmental Sustainability of Upscaling Solar Photovoltaic Irrigation*). Measures are also required to minimize the threat of theft of solar PV equipment.

Solar PV irrigation has the potential to significantly enhance agricultural production and farm incomes. However, the effectiveness of irrigation depends on other factors such as availability of complementary inputs (fertilizer, improved seeds and extension services). Moreover, these business models require strong farm and business management coupled with good market linkages for the produce. This underscores the need for a comprehensive approach, i.e., coupling solar PV technology with access to high-quality inputs, price information and crop markets.

Conclusions and Recommendations

This report assessed the potential of solar PV irrigation for smallholder farmers in Ghana, using elements of business planning and business models in tandem with a new methodology for mapping its environmental suitability. Suitability mapping revealed that solar PV technology is a promising solution to lift water—both surface water and groundwater—to irrigate an area up to 2.3 Mha. However, five major issues need to be addressed to support scaling out this technology: (i) creating greater awareness among all parties of its potential; (ii) supportive policies and institutions to encourage both public and private investments in the technology; (iii) making finance widely available at affordable prices; (iv) testing alternative business models; and (v) managing potential environmental risks.

Awareness Creation

Although we did not carry out a formal survey on awareness of solar irrigation technology, our experience suggests that few people are aware of its availability, actual costs and potential benefits. We recommend that policy makers and technology suppliers invest substantially in creating awareness of this technology through field demonstrations and campaigns. Awareness creation needs to be targeted at financial institutions, district directors, extension services and local knowledge networks. Another recommendation is that, as farmers have varying irrigation needs and purchasing capacities, experiments with multiple business models and financing schemes should be encouraged.

Supportive Policies and Institutions

Our analysis of Ghana's policies and institutions in the section *Institutional, Policy and Regulatory Context for Solar Photovoltaic Irrigation* found that while many correct policies have been articulated, implementation has lagged. This is likely handicapping the rate of uptake of solar irrigation. We recommend that the government completes the process of creating an enabling environment for investment in solar PV technology, and considers encouraging the development of domestic capacity in the manufacture and assembling of solar PV systems and accessories. We also recommend that policies supporting solar PV for irrigation must ensure optimal sizing of pumps, promote efficient irrigation practices and incentivize the cultivation of locally suitable crops. A mismatch in the capacity of a solar PV system and the size of the farm or the number of farmers using the system, as documented in the section *Financial Analysis of Two Solar Irrigation Business Cases*, may result in underutilization of the system and its failure. Finally, policy makers can do a lot to foster more rapid expansion of solar PV irrigation, including addressing the biggest bottleneck – availability of affordable finance.

Making Finance Available and Affordable

In the section *Business Model Scenarios for Upscaling Solar Photovoltaic Irrigation in Ghana*, we proposed three solar irrigation business model scenarios based on the value proposition of providing reliable and affordable access to irrigation water to smallholder farmers, especially for dry-season farming. We also proposed several alternative financing scenarios such as matching grants or partial capital subsidy from public or donor agencies, revolving fund financing schemes, and trade credits such as rent-to-own schemes. These offer promising options for smallholder farmers to gain access to the technology.

Policy makers and financiers should facilitate access to credit for farmers as well as for technology suppliers and entrepreneurs prepared to invest in irrigation service provision. From the beginning, international donor agencies and NGOs have played a key role in expanding the use of solar PV for irrigation in Ghana. The degree of private sector involvement varies across the solar PV technology supply chain. More private sector-led commercialization of the technology is evident at the import and distribution system level, while more international donor agency and NGO investment is observed at the end user or farmer level.

The existing model of funding the initial investment cost of solar PV technology through donor or government subsidy schemes might be required to stimulate demand; but these subsidy schemes should be properly targeted toward resource-poor farmers (including women). Furthermore, subsidy schemes can be adapted to include a risk-sharing mechanism through partial funding or through a revolving fund approach. Donors can establish partnerships with local banks to offer low-interest loans targeting a large number of different smallholder farmers. Other approaches tested in other countries such as the rent-to-own model where technology suppliers provide the technology on loan to farmers, with the solar PV system as collateral, can also be adapted.

Testing Alternative Business Models

The two empirical case studies presented in the section *Financial Analysis of Two Solar Irrigation Business Cases* show that different business models can be designed to implement solar irrigation for smallholder farmers. The direct funding model is implemented by an individual farmer or agribusiness cultivating high-value crops and is driven by profit maximization or cost minimization. In contrast, the cooperative model is implemented by a group of smallholder farmers through an implementing agency (e.g., an NGO). The cooperative model addresses the capital and O&M cost challenge. However, once the technology is installed, success depends on a number of factors, especially the ability of the group to manage the system collectively and the profitability of crop production.

One dimension that needs further exploration in Ghana is designing systems for multiple water uses. A solar-powered pump owned by an individual smallholder may be underutilized, pumping for a short period only during the dry season. The underutilization could be addressed if the farmer rents the pump to neighbors or provides pumping services to them. In some areas, this could lead to the emergence of a water market. Another possible solution is to design systems to provide water for other purposes as well: domestic supply, livestock watering, and non-agricultural productive uses. Another is to use the solar panels to generate electricity for other purposes, such as recharging batteries or operating other machinery. In the future, selling surplus power to either a community electricity grid or to the national grid may become an option.

The other dimension we have discussed, but not fully explored, is the provision of water for irrigation and other uses as a service provided by an entrepreneur. This type of business has been documented in other African and Asian countries (Merrey and Lefore 2018a), and needs to be tested in Ghana. It may prove to be a viable alternative to individuals purchasing expensive pumps and may create new jobs.[16]

The initial investment costs of the two business cases were funded fully or partially by donor seed money. This is representative of most of the solar PV technologies installed in small farms in Ghana to date and emphasizes the important role that international donor agencies play. Although the Groital direct funding business case is not a small-scale farm in the context of Ghana, it does illustrate how donor seed money can enable farmers to transition to commercial agribusinesses. The key to the success of this business model is having good market linkages to obtain a positive return on investment. The financial results show that farm income is high enough to recover the

[16] The 'Hello Tractor' model from Nigeria, a business that links owners of tractors with those needing services, and the 'Uber for the farm' case are interesting models applicable to pumping services. Refer https://www.hellotractor.com/home (accessed on November 24, 2019) and Merrey and Lefore (2018a).

total investment cost of the system, indicating that with access to finance such as bank loans from financial service providers, this business model is financially feasible. However, for the interim period, donor support is needed because financial service providers in Ghana generally do not provide credit for irrigation and related technologies.

In contrast, the financial results of the cooperative model showed that the farm income from the 2 ha irrigated, although positive, was not high enough to recover the initial investment cost of the system as it was both very expensive and underutilized. However, an analysis based on the full 5 ha planned to be irrigated showed that the system would have been financially as well as economically viable; the limited water source prevented full use of the system. Key challenges in the successful operation of a jointly owned solar PV system are the need for proper assessment of the water supply, cooperation among farmers on irrigation scheduling, strengthening of agricultural advisory services, implementing sustainable tariff setting and revenue collection, and measures to prevent technology theft.

Despite the difference between the two empirical cases, business models play an important role as decision-making tools to identify the conditions that will enable solar PV systems to sustainably enhance farmers' productivity and economic resilience. The business model framework takes not only the economic aspects of solar PV technology into consideration but also environmental impacts.

Managing Environmental Risks

The suitability analyses presented in the sections *Business Model and Suitability Mapping Approaches* and *Analysis: Suitability Mapping for Solar Pump Irrigation* show that vast areas in Ghana are suitable for solar PV irrigation using groundwater or, to a lesser degree, surface water resources. Most of the suitable areas are located in the northern parts of the country. For groundwater suitability, a key constraint is the aquifer condition; the best groundwater resources are in the northeastern parts of the country. Our suitability analysis focused on the availability of water resources; however, more detailed studies are needed to identify the safe yield compared to the potential irrigated area. The potential benefits of expanding solar PV pumping in Ghana could be limited or even nullified, if not managed carefully. Achieving a reasonable and sustainable balance will not be easy. However, the following practical steps emerging from the study can be taken into consideration:

- Careful study of aquifers to identify their sustainable safe yield before drilling wells and installing pumps.
- Identify the current status of water use and demand for agriculture as well as other uses to ensure water security for all users.
- Conservation of water by growing drought-tolerant crops, adopting irrigation technologies that reduce water use (e.g., drip irrigation), and improving irrigation scheduling and water productivity.
- Using irrigation solar panels to generate electricity for other purposes.
- Encouraging sustainable agroecological practices that maintain land and water resources and biodiversity.
- Incentivizing farmers on best management practices for nutrient management and reducing inputs such as pesticides.

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Annex 1. Input Data for Suitability Maps.

Depth to bedrock was used as the only soil suitability parameter in our study, in order to minimize limitations of the soil type since different crops with different soil requirements are grown across the country. Incorporating this soil parameter ensures that the final selected areas for PV pumps had enough soil to anchor in plants well. The total annual rainfall data for the period 2001–2012 was downloaded from the WorldClim[17] website and averaged to obtain the total annual precipitation (Fick and Hijmans 2017).

Three maps on aquifer characteristics – aquifer productivity, storage and depth to groundwater – developed by the British Geological Survey (BGS) (MacDonald et al. 2012) were used in this study. The aquifer productivity map shows the interquartile range of borehole yields from actual wells drilled. The groundwater storage map was estimated from the saturated aquifer thickness and effective porosity as determined from secondary data sources. Finally, the depth to groundwater was developed empirically by considering the aquifer type, rainfall and proximity to river (MacDonald et al. 2012). It must be noted that while the data downloaded from the BGS site was labeled as having 5,000 m resolution, the only available data for groundwater depth, productivity and water storage were in 9,000 m resolution.

A finished map of the average travel time (in hours) to the nearest town with a population of at least 100,000, developed by HarvestChoice and IFPRI (2016), was downloaded. It was assumed that towns meeting this population threshold will also have markets for farm produce and will also be more likely to be able to sell solar pumps and their accessories.

The study calculated the annual solar irradiation from the digital elevation model (DEM) using the 'Area Solar Radiation' tool in ArcGIS. This calculates the maximum theoretical solar irradiance (watt hours [Wh]/m^2) on a given surface with a particular tilt angle as a function of the day of the year and latitude. To reduce the computational time while accurately representing the differences in sunshine over the course of a year, solar irradiation was calculated at 0.5-hour intervals for days 1, 45, 90, 135, 180, 225, 270 and 315 in the year. The outputs were averaged and then multiplied by 365 to obtain the total annual solar irradiation.

[17] https://www.worldclim.org/

Table A1. Original and derived spatial data used in PV pump suitability mapping.

Data category	Data	Spatial resolution (m)	Source	Year
Topography and soil suitability	Elevation	90	Shuttle Radar Topography Mission (SRTM) 90 m DEM	2017
	Depth to bedrock	250	https://www.isric.org/projects/soil-property-maps-africa-250-m-resolution (Hengl et al. 2017)	2017
Climate	Rainfall	900	WorldClim (http://www.worldclim.org/) (Fick and Hijmans 2017)	2005
	Solar irradiation	90	Derived from DEM	2017
Surface water resources	Small reservoirs	Vector	Digitized from aerial images using Google Earth Pro (Google Inc. 2018)	2018
	Rivers Inland valleys	Vector 231	Tropical and subtropical wetland distribution	2016
Groundwater resources	Groundwater depth Aquifer productivity Groundwater storage	9,000	British Geological Survey http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/mapsDownload.html (MacDonald et al. 2012)	2012
Land use and protected areas	Land use and land cover Irrigated land	300	European Space Agency (ESA) (http://maps.elie.ucl.ac.be/CCI/viewer/download.php) Climate Change Initiative (CCI) land use and land cover	2015
	Protected areas National park	Vector	International Union for Conservation of Nature (IUCN) database	2010
Infrastructure and population	Proximity to town	10,000	HarvestChoice and IFPRI 2016	2010

Annex 2. List of Key Institutions in the Renewable Energy Sector in Ghana.

Institution	Functions
Policy and regulation	
Energy Commission	Advises the minister of power on energy policy and licenses; regulates and monitors energy service providers; develops national energy plans.
Ministry of Sanitation and Water Resources	Responsible for water subsector developments; facilitates private sector participation in the provision of improved technologies and approaches for effective provision of water.
Public Utilities Regulatory Commission (PURC)	Regulates tariffs for the purchase and transmission of electricity from renewable energy sources.
Environmental Protection Agency (EPA)	Monitors and enforces environmental policies.
Ghana Investment Promotion Centre (GIPC)	Promotes investments in Ghana by providing an enabling environment for investment.
Implementation	
Volta River Authority (VRA)	Generation and transmission of electricity.
Bui Power Authority (BPA)	Generation and transmission of electricity.
Ghana Grid Company (GRIDCO)	Transmission of electricity.
Electricity Company of Ghana (ECG)	Distribution of electricity in southern Ghana.
Northern Electricity Distribution Company (NEDCo)	Distribution of electricity in northern Ghana.
*Nongovernmental organizations**	
Association of Ghana Solar Industries	Promotes and raises the profile of the solar industry, improves quality, and develops standards and training.
Energy Foundation	Promotes energy efficiency measures and renewable energy technologies.
NewEnergy	Develops and implements clean energy initiatives.
Kumasi Institute of Technology, Energy and Environment (KITE)	Energy policy studies and analysis, and clean energy enterprise development.
Centre for Empowerment and Enterprise Development (CEED)	Promotes technologies that offer engineering solutions to climate change and energy poverty.
iDE	Implements market-oriented solutions to enable farmers to access improved irrigation technologies, including solar PV water pumps.
Education and research	
The Energy Center, Kwame Nkrumah University of Science and Technology (KNUST)	Research, development, demonstration and educational activities in energy technology, policy and management.
University of Energy and Natural Resources (UENR)	Training in science, technology and management of energy and natural resources.
Council for Scientific and Industrial Research (CSIR)	Implementation of government policies on scientific research and development.

Source: IRENA 2015.

Note: * This list of NGOs is not exhaustive. It only presents some examples of the type of interventions implemented by NGOs.

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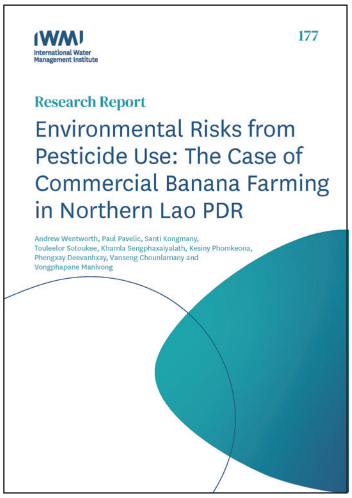

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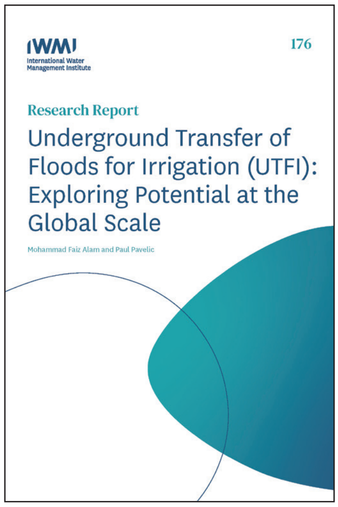

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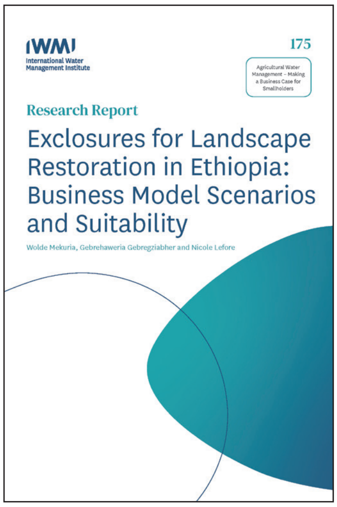

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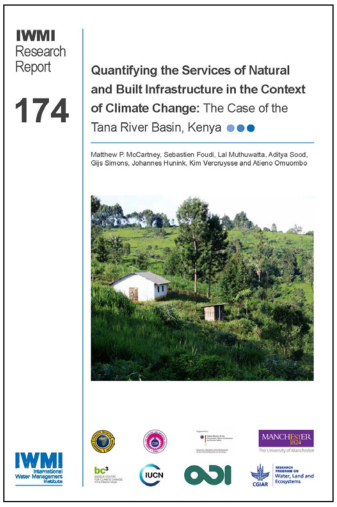

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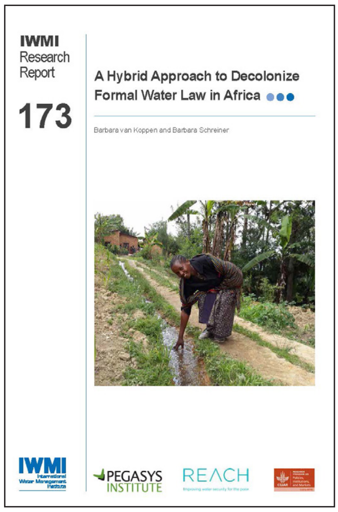

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Pelawatta
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Sri Lanka

Mailing address
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Colombo
Sri Lanka

Telephone
+94 11 2880000

Fax
+94 11 2786854

Email
iwmi@cgiar.org

Website
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