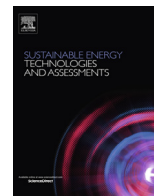




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Increasing productivity through irrigation: Problems and solutions implemented in Africa and Asia

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ABSTRACT

The United Nations Food and Agriculture Organization predicts that between 2005 and 2050 global food production will need to increase 70 percent to meet the demand of the world's growing population. Simultaneously, climate change threatens to disrupt growing seasons and rainfall across the globe. For food production to keep pace with population growth and resist the effects of climate change, the expansion of irrigation to non-irrigated farmland is critical. Innovative, affordable, and easy-to-implement technologies are needed for smallholder farmers to irrigate efficiently, mitigate greenhouse gas emissions, and help adapt to the effects of climate change. This paper presents three major interconnected problems inhibiting the spread of irrigation in Asia and Africa: lack of access to water, lack of access to energy, and lack of access to finance. This paper also discusses how these problems are interconnected, complicating the use of technological solutions to address these problems. Several approaches to address these three interconnected problems in Asia and Africa are presented in this paper. Through the examination of seven case studies in Asia and Africa, this paper finds that new irrigation products and services must include appropriate technology, sales, service, financing, and revenue collection in order for them to be widely adopted by underserved communities.

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Background

The United Nations predicts that between 2005 and 2050 more than half of the global population growth will occur in Africa, which translates to an increase of 1.3 billion people in population [1]. In the same timeframe, Asia will have added another 0.9 billion [1]. The Food and Agriculture Organization of the United Nations (FAO) predicts that global food demand is going to have to increase by 70 percent between 2005 and 2050 just to keep up with expected global population growth with a resulting direct effect on agricultural water use [2]. Historically and globally, agricultural intensification has been largely accompanied with the increased energy and water inputs to grow, process, and distribute agricultural products. As a result, there is growing concern that increasing agricultural production will cause an even greater demand for fossil fuels worldwide and result in unsustainable water withdrawals

that could contribute to greater food insecurity [3]. FAO estimates that agriculture currently accounts for 70 percent of global freshwater withdrawals [4]. With the projected increase of the world population, climate change will apply further stress on water resources in regions where water availability and accessibility are already critical limiting factors for food production. Extreme weather events such as heat waves, droughts, floods, storms, changes in temperature, and sea level rise will have significant impact on crop yields, agricultural productivity, and availability of arable land [5]. A large number of countries that depend on agriculture as a major contributor to their GDP are in Africa and Asia. Increasing water scarcity and drought resulting from climate change in these countries will adversely affect economic growth, endanger local farmers' livelihoods and threaten regional food security in the process [3]. Irrigation plays a crucial role in food production and improving food security by not only allowing achievement of full crop production potential in a given growing environment, but also by fighting pests through products diluted in water, protecting sensitive crops from frost, adding nutrients

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that are dissolved in the water, improving land physical properties, and removing excess salinity from the soil [6].

There is an enormous potential to improve agricultural productivity with irrigation in areas that depend on rainfall, such as Sub-Saharan Africa and large parts of Asia. The FAO reports that while only 20 percent of the global arable land in use is irrigated, it supplies 40 percent of the total food grown worldwide, producing more than 2.5 times the yield of rainfed crops [7]. Africa irrigates just over 5 percent of its available cultivated land, representing the lowest percentage of any continent [8]. As a result, it is also the continent with the highest potential for irrigation expansion, with about 42.5 million hectares of unirrigated land [9]. Asia's irrigation rate is higher at 41 percent, but due to Asia's size the remaining unirrigated land also represents a large, untapped demand [7]. Irrigation allows both higher yields within a crop cycle and, if climate allows, multiple crop cycles in a single growing season. As a result, large quantities of crop production occur on small areas of irrigated land.

There are multiple irrigation methods used by farmers worldwide, but most were developed for expediency and economic value generation rather than reduction of environmental impact and water efficiency. Use of pumps powered by increasingly expensive fossil fuels to flood or partially flood fields is still a common irrigation method that is water inefficient and pollutes the environment. Many of the poorest, off-grid farmers irrigate manually with buckets of water because they cannot afford to purchase or rent a fossil fuel-powered pump. Frequently, more sophisticated irrigation methods that cause little or no environmental degradation exceed the affordability of most smallholder farmers. As a result, the demand for inexpensive and clean technologies to replace traditional irrigation methods are rising in developing countries. Farmers need better access to innovative, affordable, and easy-to-implement technologies in order to irrigate efficiently, mitigate greenhouse gas emissions, and help adapt to the effects of climate change.

Today there is an increasing number of technology innovators working to develop products and services to address the irrigation needs of subsistence and smallholder farmers in the developing world. For example, Burney et al. discuss how solar PV drip irrigation significantly augments both farmers' income and family nutritional intake, and is cost effective compared to alternative technologies in the Sudano-Sahel region of Africa [10]. Haile et al. detail the advantages and potential pitfalls observed with smallholder drip irrigation technology being implemented in East Africa [11].

There are several barriers that have hindered the successful development, implementation, and commercialization of workable irrigation solutions with smallholder farmers in Africa and Asia. These barriers revolve around the farmers' lack of access to water, reliable energy, financing, knowledge of irrigation benefits, and training. This paper focuses on lack of access to water, reliable energy, and financing. This paper introduces each of these three problem and presents several technology innovators that are currently working on solutions to these barriers. This paper does not address problems such as lack of access to market information, good quality seeds, or reliable crop preservation techniques because these are barriers to farm profitability, not barriers to widespread irrigation usage. Where appropriate, the different technologies and their effectiveness are compared.

Methodology

This paper discusses the three most common challenges that off-grid, smallholder farmers face when irrigating their fields: lack of access to water, lack of access to reliable energy, and lack of

access to financing. Each challenge is illustrated with multiple innovators who are developing appropriate technical solutions. The innovator case studies outlined in this paper are a result of the close partnership between the authors of this paper and technology innovators supported by the *Powering Agriculture: An Energy Grand Challenge* (PAEGC) initiative as described below in the Funding Section. Information on each innovator's technology and business model is collected from a variety of information and data submitted as part of their participation in Powering Agriculture. Metrics are calculated by the authors using data that was submitted by the innovators and verified by the authors through site visits, interviews, and publicly available information. Each of these brief case studies includes an introduction to the technology and subsequent challenges encountered by the technology innovators.

Lack of access to water

ECO Consult, an innovator that started developing solar PV hydroponic farms in Jordan in late 2013, and the Institute of University Cooperation (ICU), a developer of solar PV drip irrigation systems in Lebanon and Jordan, are both finding ways to maximize efficient water usage on farms in water-scarce countries.

Lack of access to energy

Both International Development Enterprises (iDE) and KickStart International are developing new low-flow, solar PV irrigation pumps that address lack of reliable energy access in off-grid farms in Kenya, Nepal, and Zambia.

Lack of access to financing

In an effort to bypass the need for farmers to access financing to purchase irrigation, both The Earth Institute at Columbia University and Claro Energy are developing irrigation service models in Senegal and India. Another model of providing financing to farmers is to connect the farmers with third-party financiers which is being pursued by Futurepump in Kenya.

Barriers to irrigation growth

Lack of access to water

Farming is particularly challenging in water scarce climates, and irrigation is a necessity when rainfed lands are not productive enough to support the population. In such locations, inefficient irrigation must be minimized. Unfortunately, traditional crop selection and irrigation practices that have developed over time in a water-scarce environment may be out of sync with current needs for water conservation. Farmers may concentrate on water-intensive, low value crops rather than maximizing the value generated from every drop of water. They may also use inefficient irrigation techniques such as flood irrigation and over-fertilization. As ground water is the most readily available source of water in these areas, inefficient irrigation and over-fertilization practices exact a heavy price on the environment through dropping aquifer levels, increased soil salinity, and nitrate contamination of surface and ground water. As the environment is degraded and farm productivity is affected, both food security and the economy suffer in a vicious self-reinforcing cycle.

In developing countries such as Jordan and Lebanon, extreme water shortages are recognized as the greatest challenge in the agriculture sector. Jordan has extremely low per capita fresh water availability and large parts of Lebanon's water resources are not exploitable [12]. Where water is available, large pumps are required

to lift water from deep underground. The agriculture sectors in these countries are struggling to meet the nations' food demand as a result of population growth and maintain the sustainability of their water resources. Starting in late 2015, ICU initiated partnerships with solar panel suppliers, pump and drip irrigation suppliers, and agricultural financing companies in Jordan and Lebanon to develop several solar PV drip irrigation systems for farmers with at least 1 ha of productive land. The solar array sizes of the systems range from 4 to 7 kW based on observed water table depth of up to 100 m, flowrates between 5.5 and 14 cubic meters per hour, and a desired price point between US\$20,000 and US\$25,000. ICU's pilot of 6 farms was over-subscribed, suggesting that smallholder farmers are able and willing to pay for cutting edge water-saving technology. With the ICU irrigation system, farmers will increase farm profitability through reduction of water needs and fertilizer cost by converting from furrow irrigation and broadcast irrigation to drip irrigation and fertigation (the process of introducing fertilizer to plant roots through irrigation water). Careful control of fertigation decreases the risk of over-fertilization.

ICU's current work in Jordan is based on small-scale pilots conducted in Jordan between 2013 and 2014 for the ENSIAP¹ project, and in Tunisia between 2012 and 2015 for the ACCBAT² project. Previously in Jordan, ICU measured the reduction in water and fertilizer usage over conventional irrigation with 20 farmers who tended approximately 0.1 ha of land each. The results of the ENSIAP drip irrigation pilot can be found in Table 1. ICU also found that fertilizer use, as measured in kilograms per square meter, decreased by –31%. In Tunisia, roughly the same water reduction was observed; however, the ACCBAT project was using treated wastewater for irrigation which make the fertilizer reduction and increased farm productivity calculations not comparable to the Jordan pilots.

Focusing solely on Jordan, ECO Consult has developed a solar PV hydroponic farming concept for rural Jordanian farmers because of the technology's capability to grow high-value crops such as fruits, vegetables, flowers, and herbs while using significantly less water than traditional soil farming. Research has found that through the use of water recycling, hydroponic lettuce farming can use as little as 10 percent of the water consumed by soil cultivation of lettuce [13]. In addition to reduced water consumption, the controlled environment that hydroponics offers farmers reduces fertilizer usage [14] and pesticide usage [15]. Through the use of indoor lighting, hydroponics would also enable Jordanian farmers to extend growing seasons [16]. Hydroponic farming would increase a farm's productivity, but a drawback is that it requires significant technical skill and capital [13]. Table 1 shows the percent change of select parameters over traditional farming techniques, as recorded by ECO Consult's demonstration farms. While ECO Consult did not report changes in fertilizer consumed when switching from soil cultivation to hydroponic cultivation, they did report that fertilizer spending per square meter, measured in Jordanian dinars, did increase +153% and +165% for lettuce and pepper respectively.

Through the installation and operation of demonstration farms, conducting training workshops, and connecting farmers to markets, ECO Consult has been able to disseminate the benefits of hydroponic farming throughout the Middle East.

Lack of access to reliable energy

An estimated 1.2 billion people, or 17 percent of the global population [17] do not have access to reliable electricity, and fossil fuel

price volatility can quickly make irrigation too costly to operate. Irrigation requires affordable, reliable, and easily accessible sources of energy to run the pumps that lift and transport irrigation water. The lack of access to reliable energy for irrigation is one of the factors that has hindered the productivity, profitability, and efficiencies of farm and agribusiness operations. One solution that many innovators turn to is solar PV pumps. Solar pumps have four advantages: (1) solar arrays are modular in size, which allows for systems to be easily sized for any pumping power demand, (2) solar pumping systems can operate without the need for batteries, which reduces system cost and maintenance, (3) solar energy is not subject to the cost volatility associated with fossil fuels such as diesel, and (4) solar pump performance is less dependent on optimal site location, unlike other renewable energy sources such as wind or hydropower. The two innovators described in this section, iDE and KickStart International, are seeking to implement and scale their solar PV pumping alternatives to maximize crop productivity and increase crop value, scale down dependence on rainfall and weather conditions, and increase the monthly income of unelectrified farmers. Both innovators focus on bringing low-cost, low-power pumps to farmers who lack access to the grid or to diesel-powered pumps. In contrast to some of the pumping solutions presented in Section "Lack of access to water", these pumps are designed for use with surface or near-surface water with maximum depths of 7 m and consume less than 100 watts.

The Sunflower pump was initially conceived in 2007 as a steam-powered irrigation pump, but a Powering Agriculture-funded joint effort initiated in 2013 between iDE and the PRACTICA Foundation—a Dutch organization that develops low-cost water, energy, and sanitation technologies—redesigned the pump to be powered by solar photovoltaic arrays. iDE's connections to off-grid, farming communities in Nepal and Zambia provided venues for field testing the pump prototypes. As the developer of the original steam-powered Sunflower pump design, PRACTICA continued in its role as technical designer. Futurepump later joined the iDE and PRACTICA partnership as the Sunflower pump's manufacturer and African distributor. The Sunflower pump has subsequently undergone five design iterations, and the consortium of Futurepump, iDE, and PRACTICA continues to address any design issues as the three entities have moved towards global commercialization of the Sunflower pump.

Coupled with iDE's ultra-low pressure irrigation kit to optimize water efficiency, the Sunflower pump is specially designed to irrigate fields smaller than 1 ha. Combining the Sunflower pump with drip irrigation accomplishes two tasks simultaneously: reduction of pumping power and elimination of high flowrates associated with broadcast or flood irrigation. Important performance metrics for the Sunflower pump can be found in Table 2. The Sunflower pump is designed to be a low-flow irrigation solution to utilize low or slow production wells that would cause higher flow electric or diesel pumps to surge or run dry. iDE's low pressure drip irrigation system is also cheaper to manufacture than other drip irrigation systems.

There are two hurdles that iDE and its partners are currently tackling as they bring the Sunflower pump to the global market: changing farmers' irrigation habits and product quality control. Transitioning farmers to lower flow pumping solutions has posed a problem for iDE. Most farmers that use irrigation pumps are acquainted with high flow pumps that satisfy their daily irrigation requirements in a few hours. Even farmers that do not own diesel or electric pumps are familiar with their high flowrates, and they expect the same from the Sunflower pump. However the low flow-rate of the Sunflower meets a farmer's irrigation needs over the course of the day rather than hours. This has forced farmers who transition to Sunflower pumps to change their daily irrigation habits. In response, iDE is focusing on developing community busi-

¹ Improving the Environmental Sustainability of Irrigated Agricultural Production in Lebanon and Jordan.

² Adaptation to Climate Change through Improved Water Demand Management in Irrigated Agriculture by Introduction of New Technologies and Best Agricultural Practices.

Table 1
Percentage change over traditional irrigation and fertilization methods.

	ICU	ECO consult		
	All crops	Thyme	Lettuce	Pepper
Crop production [kg/m ²]	+13%	+450%	NA	+18%
Water usage [L/m ²]	–33%	–44%	–51%	–54%

Table 2
Low-power pump performance metrics.

	KickStart International			iDE
	Money Maker	MoneyMaker Max	Encap Solar Pump	Sunflower
Power Source	Human	Human	Solar	Solar
Max Flowrate	2200 L*hr ⁻¹	3600 L*hr ⁻¹	900 L*hr ⁻¹	2200 L*hr ⁻¹
Max Suction Lift	7 m	7 m	5 m	7 m
Array Size	0	0	45 W–60 W	48 W
Weight	4.5 kg	16 kg	6.8–13.6 kg	20.5 kg
Capital Cost	\$60–\$90	\$115–\$140	\$180–\$220	\$650–\$750

ness facilitators and training regional technicians who act to influence customers' irrigation behavior. iDE is especially targeting key farming community leaders who can be converted into evangelists to spread the benefits of the Sunflower pump and provide instruction on its optimal use. iDE is also striving for ever-increasing levels of quality control from their manufacturing partners to ensure that every customer gets a Sunflower pump that provides a low-cost, high-value experience. To ensure every product revision they enact fulfills the needs of their customers, iDE has carried out field testing on five generations of the Sunflower pump in Zambia and Nepal to provide extensive feedback to their manufacturing base in India and global design team.

Kickstart International has spent 25 years developing and selling off-grid irrigation pumps that help transform subsistence farmers into financially stable growers of high value crops. KickStart has previously garnered great success and acclaim developing, marketing, and selling human-powered pumps such as the MoneyMaker Max treadle pump and the MoneyMaker hip pump to over 260,000 farmers in Africa. These two pumps are designed to have very short payback periods by encouraging customers to increase incomes through irrigation of small plots of high value fruits and vegetables. One drawback to human-powered pumping is the limited area that can be irrigated due to fatigue and power output limitations of the operator. In an effort to appeal to farmers with larger irrigation needs, KickStart started developing solar PV irrigation solutions in mid-2016 with Encap Technologies, a specialist in thermoplastic encapsulation of pumps and DC motors. The solution is a low-cost, low-power pump designed to irrigate up to 0.2 ha a day using surface water sources such as rainwater catchments, rivers, and ponds. Together with Encap Technologies, KickStart International is focusing on reducing pump cost through a redesigned pump and motor that is both more robust and easier to manufacture. To further create value for their customers, KickStart International is considering providing additional electricity access in the form of 5-volt phone charging ports on their array, allowing farmers to charge phones, lanterns, and other off-grid appliances. A comparison between KickStart International's human-powered and solar PV pumps is included in Table 2.

As a result of their experience gained during previous solar pump development iterations, KickStart has identified important product features that customers desire. A desire for solar system and pump mobility has led them to incorporate a lightweight pump and design a wheeled or folding solar array. KickStart is also planning to significantly increase total system efficiency so that panel array size will be at most 50 percent of the size of initial prototypes. The smaller array will increase portability and decrease

system cost when compared to KickStart's initial solar design. They are also exploring ways to increase daily pump runtime, especially on cloudy days, through use of Maximum Power Point Trackers and other electronics.

It is interesting to note that while KickStart International's human-powered pumps are much cheaper than the solar pumps described in Table 2, solar pumps allow farmers to work on other tasks while fields are being irrigated. All pumps provide the same maximum suction lift, between five to seven meters, however the pumps provide slightly different flowrates. In fact, the MoneyMaker Max pump provides the highest flowrate of all the pumps discussed in Table 2. This assumes that the human being powering the pump is able to provide the necessary power to maintain said flowrate; as the pump operator tires, the output of the MoneyMaker and MoneyMaker Max will decrease. While the solar pumps being developed by KickStart and Futurepump may not provide superior performance when compared to treadle pumps, they do provide consistent performance throughout daylight hours. The farmer is paying for the ability to conduct other tasks during the day rather than operating a treadle pump all day.

Lack of access to financing

Although modern irrigation increases yields and improves livelihoods for subsistence and smallholder farmers, their financial capacity to invest in solar PV irrigation solutions remains constrained. These farmers usually have limited cash flows and rarely produce enough surplus capital to purchase capital-intensive technologies such as solar pumping systems [18]. Where long-term financing is readily available, it offers farmers the opportunity to leverage expected future cash flows from improved irrigation to finance the purchase of the equipment today. However, small farmers' access to long-term affordable finance is limited in developing countries throughout Africa and Asia.

Investors and financial institutions are hesitant to extend financing for solar pumping due to three types of risks: technological, operational, and financial. *Technological risk* relates to equipment malfunction or failure, which prevents the farmer from realizing the expected additional cash flows as a result of irrigation. *Operational risk* captures the probability of systems being operated incorrectly and thereby failing to enhance agricultural productivity and improve cash flows. *Financial risk* is linked to the failure of the farmer to pay the required loan installments or service fees. The perception of these three risks is higher in developing countries where rural banking and microfinance institutions have limited experience with evaluating and funding solar pump-

ing and photovoltaics in general. They are particularly reluctant to offer financing to small farmers whose creditworthiness is reduced due to the seasonality and unpredictability of their cash flows.

The innovators discussed in this paper have adopted business models that mitigate the aforementioned risks so that farmers can access modern irrigation in India, Kenya, and Senegal, using credit rather than savings. In doing so, the innovators are giving farmers the opportunity to exit the poverty cycle and accelerate the penetration of irrigation into under-irrigated regions within Africa and Asia. The models fall in two main categories: Pay-as-You-Go (PAYG) and asset financing. While different in design and risk allocation, these models do not require significant upfront capital investment from the farmers who instead pay for the irrigation service or purchased equipment from improved cash flows.

Pay-as-You-Go service model

Under the PAYG model, the farmer does not own the solar pumping system. The assets are owned by a service provider who also assumes responsibility for the operations and maintenance of the equipment. Farmers purchase irrigation services on-demand from the service provider in exchange for usage- or time-based tariffs. Over the life of the project, these tariffs allow the service provider to recover its capital cost, operational costs, and a return on investment.

The PAYG model mitigates technological risk by assigning the procurement and ownership of the physical assets to a specialized service provider which typically possesses a sufficient level of technical sophistication to ensure the quality of the installed technology. Similarly, the service provider reduces the operational risk by instituting efficient operational protocols and hiring trained personnel to manage and maintain the assets. The financial risk is mitigated through the utilization of transparent billing and collection systems, often in the form of prepaid metering. Investors and financial institutions provide funding directly to the service provider to invest in assets that will generate sufficient cash flows to service the debt financing and distribute dividends to equity investors.

The Earth Institute of Columbia University (EI) started developing a micro solar utility for small-scale irrigation for farmers in Senegal in late 2013 and uses a PAYG component in their business model. The innovator has implemented three pilot micro-utilities serving seven farmers each. To mitigate technological risk, EI used standardized solar design and off-the-shelf components. The technological risk is further reduced by using wires to distribute electricity to power individual AC pumps on the farmers' lots instead of distributing water through pipes or channels. Furthermore, an engineer belonging to the local partner Millennium Promise's Millennium Village Project is available on-call to address equipment malfunction or failure. To reduce operational risk, an irrigation cooperative was organized with support from Millennium Promise to own and operate the micro-utilities. The cooperative staffs each micro-utility with an attendant who operates and maintains the system. The attendants are trained by EI to ensure that they are qualified to perform their duties. The continued involvement of the local partner Millennium Promise provides insurance against operational errors through technical oversight. The irrigation cooperative also plays an important role in mitigating the financial risk of late or non-payment. The cooperative can apply social pressure on non-paying farmers. To further manage the risk of non-payment, EI introduced a prepayment system. Initially, EI planned to automate the system by using smart meters. However, EI eventually modified its approach due to the level of effort required to properly develop an automated metering solution. To overcome this challenge, EI devised an alternative, and locally suitable, payment method. Farmers prepay for pump usage at the cooperative. They then take their payment receipt to the attendant in the field

who manually turns on the pump and records each transaction. This system has worked well, further proving the importance of the irrigation cooperative in reducing both operational and financial risk.

Claro Energy also offers a PAYG irrigation service. However, in contrast to the Earth Institute's stationary irrigation micro-utility, Claro developed a mobile solar irrigation system consisting of a portable solar array and pump mounted on a trolley in mid-2015. The company has mitigated the technological risks of this mobile model by using standard off-the-shelf components with proven performance track records. Technological risk is further reduced through the distributed and mobile nature of Claro's solar pumping trolley fleet, which compartmentalizes failures. The effect of one trolley failing will not endanger Claro's financial stability. Claro has adopted a "virtual utility" model, under which it owns and operates the systems and rents them to farmers for single irrigation sessions. To manage operational risk, the company developed an automated booking, dispatching, and monitoring system intended to reduce human error. The system allows the company to log important data that helps reduce operational inefficiencies, including liters of water pumped, hours of operation, kWh of electricity generated, crops grown, cultivated area, irrigation cycle number, and GIS coordinates. The operational risk is further reduced by dispatching trained operators with the units and storing the trolleys in centralized depots owned by the company to prevent damage and theft. To reduce the financial risk of non-payment, Claro utilizes a transparent prepayment system consisting of automated call centers and mobile payment technologies. To reach a wider group of farmers, prepayments can be made through mobile money, credit card, or a deposit at a Claro Energy depot. Cash transactions at point of use are avoided at all costs in order to avoid the risk of dispatching a unit to a farmer who is not able to pay. The virtual utility model mitigates another financial risk relating to declining cash flows resulting from asset underutilization. If demand for the service declines within one area, the mobile units give the company the flexibility to cover a wider range or move to a completely new area with better demand for the service.

Asset financing

With asset financing, farmers' access to finance is improved through a partnership between a technology provider and a financial institution. The farmer buys an irrigation system from the technology provider using a loan from the financial institution to be repaid in regular installments. The partnership mitigates risk by allowing each partner to play to its strengths. The financial institution assumes the financial risks such as borrower delinquency and defaults by holding the debt on its balance sheet. It mitigates these risks by applying a rigorous creditworthiness assessment to potential customers. For its part, the technology provider assumes the technological risks by offering aftersales services and product warranties. It manages these risks by applying rigorous quality control at the factory and the possibility to offer full training to distributors and customers.

Futurepump manufactures the Sunflower pump discussed in Section "Lack of access to reliable energy". In early 2016, Futurepump started laying the groundwork to provide customers access to modern irrigation through asset financing rather than PAYG services. The Sunflower pump has gone through an extensive product development process of five iterations, significantly reducing the probability of product failure. Furthermore, the company offers a 12-month parts and labor warranty on its product. To reduce operational risk, farmers who buy the pump receive training on how to properly operate it and how to adjust their irrigation practices to low-flow irrigation.

Futurepump found designing attractive asset financing products, especially through banks, extremely challenging. Initially,

Table 3
Technical and financial component developers.

	Sunflower Pump	KickStart Solar Pump	Earth Institute's Micro-Solar Irrigation Utility	Claro Energy's Solar Trolley
Technical Component Developer(s)	PRACTICA: Design iDE: Field Testing Futurepump: Manufacturing	KickStart Encap	Earth Institute	Claro Energy
Financial Component Developer(s)	Futurepump Equity Bank	Angaza Design	Earth Institute Millennium Promise	Claro Energy

Futurepump had planned to offer Sunflower pump on finance for a 30 percent down payment through a partnership with a leading Kenyan bank. However, in practice this proposition has proved difficult to implement. Despite agreeing to a higher down payment of 50 percent, regional credit officers are still hesitant to approve loans for small farmers.

While Futurepump implements a marketing and outreach program to educate the regional credit officers about the Sunflower, it has been working with a local cooperative, Safe Produce Solution, to pilot an asset-financing scheme with a harvest-timed payment plan. The cooperative financed the purchase of 44 pumps for its members using a revolving fund created with support from the Powering Agriculture initiative. This pilot demonstrates that agricultural cooperatives can play an important role in extending finance to rural farmers. Cooperatives can act as intermediaries between financial institution and small farmers by administering, bundling and guaranteeing loan facilities.

Discussion

Water scarcity, energy availability, and access to finance are mutually compounding problems that can lock a farmer into a poverty trap. The combination of all three problems can lead to the deterioration of the community's food security and the local agriculture-based economy. All of the technology innovators presented in this paper recognize that the issues of water access, energy access, and finance access are interconnected. Both the hydroponic farming solution developed by ECO Consult and the drip irrigation and fertigation solution developed by ICU are more energy intensive than traditional rainfed irrigation or flooding irrigation. Additional energy is needed for water filtration and recycling, fertilizer production, and higher pumping pressures to access deeper water tables. Without access to energy, these solutions to water scarcity would not be viable. Similarly, efforts to develop low-cost, solar PV pumps are dependent on access to water. Both KickStart International's pump and the Sunflower pump jointly developed by iDE, PRACTICA, and Futurepump, are designed to pump from surface water sources. Pump power requirements and pump cost increase as water lift height increases, so both KickStart's pump and the Sunflower pump are limited to suction heights of 5–7 m. Without adequate access to surface water, both product development efforts would face serious hurdles.

Even if technical solutions are readily available, few farmers would be able to afford them because most farmers are not realizing sufficient profit on their harvest due to lack of access to water and energy. Access to financing is usually required to pay for the technologies that address water or energy scarcity. This forces innovators to simultaneously develop a technical product coupled to a financing method. In the case of the Sunflower pump, iDE, PRACTICA, and Futurepump each play a role in developing successive technical designs, and Futurepump is working with Kenya's Equity Bank to develop the asset financing. In addition to developing a new low-cost solar PV pump with Encap Technologies, KickStart has also partnered with Angaza Design to develop a prepaid

metering mechanism that will make asset financing of their low-cost solar pump more attractive to outside financiers. Even innovators that have focused on developing a financial product or service to support the irrigation needs of smallholder farmers also have to develop technology that supports the financial innovation. In addition to developing its mobile irrigation service, Claro Energy will continually invest time and effort into developing their solar trolley. Their trolley size and weight affect transit cost and time, and customer access. The viability of Claro's irrigation service is also affected by individual component selection like the pump, which is a compromise between trolley capital cost and water access. Lastly, Earth Institute worked with their local partner, Millennium Promise, to develop a solar micro-utility to provide irrigation services to farmers; however, EI invested a significant amount of time in developing new pump and irrigation control technology to properly match electricity generation, multiple pump operation, and irrigation demand. Table 3 shows the respective technological and financial component developers for the four mentioned innovations.

Finding local partners is extremely important, but future innovators should be cognizant of the inherent challenges that some partners bring to the project. As part of their effort to provide continuing micro-utility irrigation service after the end of their funding, the Earth Institute worked with their local partner, Millennium Promise, to develop collection and operation practices so that they can take over operation, revenue collection, and maintenance of the solar PV irrigation micro-utility. In addition to serving as a method to reduce the irrigation micro-utility's operation risk, Millennium Promise can also make it more financially attractive to a third-party investor. This is a strategy that Futurepump is actively and successfully pursuing with Safe Produce Solution. As stated in Section "Lack of access to financing", investors are wary of giving debt and equity to services that cater to farmers who have irregular income. To compound their irregular income, these farmers are not able to access debt because they do not own assets that can be used as collateral and banks find it difficult to recoup overhead costs when lending small amounts of money to farmers. The microfinance industry was developed as a way to provide banking services to the same kind of poor farmers that Earth Institute's irrigation micro-utility and Futurepump's Sunflower pump serve. By providing microcredit to its members, a local cooperative can offset the farmers' irregular income and increase the likelihood that the farmers will be able to consistently pay their irrigation bills. Thus, the presence of co-ops like Millennium Promise and Safe Produce Solution helps to reassure investors who may want to support the technology innovator.

Despite the fact that Millennium Promise increases Earth Institute's micro solar utility's attractiveness to investors, it can bring challenges that must be addressed. The community-managed utility model, as opposed to the entrepreneur-managed utility model, presents its own limitations. One study examining off-grid projects in West Bengal argued that community management of a micro-grid results in lower revenue recovery than is required for ongoing profitability, and the management organization is vulnerable to co-option by local power brokers [19]. Others have noted that com-

munity operation of microgrids is preferable, but the challenges to this governance model include: lack of technical and business skills within the management, resource mismanagement via tragedy of the commons, difficulty punishing fellow community members, corruption, and the potential for inter-community political conflict [20]. That is not to say that entrepreneur-managed micro-utilities are preferable. For-profit micro-utilities tend to be less community involved and are more likely to cherry-pick profitable customers, leaving poorer customers without the benefits of electrification [21]. When choosing local partnerships, an innovator must deliberately evaluate each partners' strengths and address any challenges that they bring to the project.

Conclusions

The approaches of the seven innovators covered in this paper support the necessity to disseminate irrigation into the off-grid regions of Africa and Asia that need it the most. Eco Consult and ICU are developing water-efficient irrigation methods in Jordan and Lebanon. Their pilots in Jordan show that both drip irrigation and hydroponics can significantly reduce water usage and increase crop production in arid climates. KickStart and the iDE-PRACTICA-Futurepump consortium are developing low-cost, solar PV irrigation pumps. The Earth Institute, Claro Energy, and Futurepump are developing methods to increase both their and their customers' access to financing. Each innovator is pursuing an integrated solution that addresses the lack of water, energy, and financing. Technology by itself is not sufficient; innovators must craft solutions that include appropriate technology, sales, service, financing, and revenue collection in order for them to be widely adopted by underserved communities. This multi-disciplinary approach is difficult for an organization to tackle single-handedly. While the innovators mentioned in this paper understand the need for holistic solutions to irrigation, it is still seductive to believe that technology can compensate for a lack of development of sales, service, financing, and revenue collection.

While some technology innovators believe that a single multi-disciplinary organization or a small group of passionate technocrats can introduce new technology into underserved and off-grid markets, the example of the Sunflower pump suggests that several sector expert organizations are required. The design, testing, manufacturing, and financing of the Sunflower pump were each carried out by separate entities that are experts in what they do. The PRACTICA Foundation provided the original steam-powered pump design and subsequent design revisions, based on feedback from iDE International and Futurepump. The pumps are manufactured by Futurepump in their India-based factory. iDE International distributed the Sunflower pumps to farmers in Nepal and Zambia willing to conduct customer testing for refinement of the pump design. Subsequently, Kenya's Equity Bank was tapped to provide asset-financing products to make the Sunflower pump affordable to Kenyan end customers. Each one of these organizations brings specialized skills and experiences to the development of the Sunflower pump and, as the Sunflower pump continues to mature, additional partners may be required to develop new areas within the Sunflower's value chain, such as service and distribution outside Kenya, to gain traction within larger markets.

All of the innovators discussed in the paper are developing low carbon, solar irrigation alternatives to diesel pumps that can drive environmentally-friendly agricultural growth in their respective communities. This agricultural growth provides economic activity in areas that need it the most and avoids further greenhouse gas emissions that drive the effects of climate change and extreme fluctuations in crop productivity.

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³ The goal of Powering Agriculture is to support new and sustainable approaches to accelerate the development and deployment of clean energy solutions for increasing agriculture productivity and/or value in developing countries. To catalyze progress towards this goal, Powering Agriculture provides funding and support to commercialize clean energy technologies and innovative business models that are designed to: enhance agricultural yields/productivity, decrease post-harvest losses, improve farmer and agribusiness income generating opportunities and revenues, and increase energy efficiency within the operations of farms and agribusinesses.

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