Solar-Powered Irrigation Systems: A clean-energy, low-emission option for irrigation development and modernization

Overview of practice

Solar-powered irrigation systems (SPIS) are a clean technology option for irrigation, allowing the use solar energy for water pumping, replacing fossil fuels as energy source, and reducing greenhouse gas (GHG) emissions from irrigated agriculture. The sustainability of SPIS greatly depends on how water resources are managed.

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KEY MESSAGES

1. SPIS can reduce GHG emission from irrigated agriculture and enable low-emission irrigation development.
2. SPIS can provide a reliable source of energy in remote areas, contribute to rural electrification and reduce energy costs for irrigation.
3. SPIS should be integrated into strong regulatory frameworks on water conservation to ensure sustainable use of water resources and avoid over-abstraction of groundwater.
4. SPIS have a high initial investment cost and need innovative financing models (or subsidies) to overcome this barrier to adoption.

Food and Agriculture Organization
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Overview of practice

In a solar-powered irrigation systems (SPIS), electricity is generated by solar photovoltaic (PV) panels and used to operate pumps for the abstraction, lifting and/or distribution of irrigation water. SPIS can be applied in a wide range of scales, from individual or community vegetable gardens to large irrigation schemes.

The essential components of SPIS are:

- a solar generator, i.e. a PV panel or array of panels to produce electricity,
- a mounting structure for PV panels, fixed or equipped with a solar tracking system to maximize the solar energy yield,
- a pump controller,
- a surface or submersible water pump (usually integrated in one unit with an electric motor), and
- a distribution system and/or storage tank for irrigation water.

In addition, semi-automated scheduling equipment can ensure that irrigation scheduling is based on crop water requirements and can optimise water use by sequentially irrigating different parts of a farm or scheme. The solar generator may also be connected to battery storage and inverter technology in order to store surplus energy for other on-farm uses, like household electrification or productive appliances. Though there are many promising developments in battery technologies, they are currently still costly, maintenance-intensive and require regular replacement. Currently, a more cost-effective option for storing energy is in the form of water pumped to an elevated tank or reservoir during sun hours.

The respective SPIS components can be combined in different configurations, depending on the site-specific biophysical and socio-economic conditions. For a comprehensive review of solar PV pumping systems and a detailed introduction to SPIS see Sontake and Kalamkar (2016) and GIZ (2016), respectively. The SPIS system should be configured by a qualified system integrator to ensure proper matching and dimensioning of its components.

The most common SPIS configuration is a solar generator on a fixed mounting structure providing electricity for a submersible pump installed in a borehole. Most solar pumps that are available on the market include an integrated monitoring system to measure the water flow, pressure and performance of the pump. They also provide an opportunity for better groundwater management.

Water is pumped either directly to the field or to a reservoir elevated a few meters above the field and stored at constant pressure before it is applied in the field. Solar pumps can support drip, sprinkler, pivot or flood irrigation methods when appropriately sized. Depending on the local conditions, a system can also include filtration or fertigation equipment.

Especially low pressure drip irrigation is often used in combination with solar pumps. The application of fertilizer through the drip irrigation system also helps to utilize fertilizers more efficiently if judiciously applied. This can help reduce on-farm expenses and the risk of non-point source water pollution from run-off and nutrient leaching. The integration of an appropriate water filter, depending on the quality of water source, is of particular importance to avoid clogging of the drippers.

Benefits of the practice

Reduced GHG emissions for water pumping: SPIS have some direct potential to reduce greenhouse gas (GHG) emissions in irrigated agriculture by replacing fossil fuels for power generation with a renewable energy source, i.e. solar energy. The operation of the water pump in SPIS is free of GHG emissions. Most GHG emissions in SPIS are related to the production and disposal of the PV panels. Life cycle assessments (LCA), taking into account these emissions in a cradle-to-grave approach, indicate a potential reduction in GHG emissions per unit of energy used for water pumping (CO_2-eq/kWh) of 95 to 97 percent as compared to pumps operated with grid electricity (global average energy mix) and 97 to 98 percent as compared to diesel-pumps (GIZ 2016). However, while these improvements are significant, the comparatively small energy demand of irrigation equipment would require very large numbers of SPIS to, for instance, replace a single 100 MW coal-fired power plant. More significant GHG emission avoidance may be achieved indirectly however through the modernisation of irrigation facilitated through SPIS: reduced pollution, more targeted fertiliser use, more precise irrigation, more benign water extraction.

Energy independence in remote areas: Solar PV can constitute a reliable source of energy for pumping of irrigation water in remote areas, in particular in areas which are not connected to the electricity grid or where regular supply of liquid fuels and maintenance services is not guaranteed. Distribution of excess electricity over local grids can also contribute to rural electrification and productive use applications.

Access to water during dry-spells and dry season: SPIS can help buffer the effects of drought and to overcome water stress during dry season when groundwater is the only available water source, or when surface water has to be hauled over long distances. When solar PV pumps replace water hauling, it can also free up a considerable amount of working time that can be invested in productive activities, e.g. dry season farming.

Improvement of income, food security and nutrition: Through the improved access to water, SPIS can help to stabilize, increase and diversify production (e.g. vegetable production including during dry season to complement staple crops). Excess produce can be sold on markets and generate income. The increased availability of food can improve food security and nutritional intake, especially of small-scale farmers and their communities. This, for instance, is well illustrated in a study by Burney et al (2009) where SPIS allowed a substantial increase of vegetable consumption in daily diets.

Challenges to adoption of SPIS

SPIS has proven to be a technically viable and competitive option with attractive return on investment. However, the high initial investment cost for equipment and installation and the lack of suitable funding schemes are big challenges to the adoption of SPIS. In many cases, solar pumps are used for only a limited time per year (i.e. for only a single crop harvest per year). Developing ways to use the energy generated during the off-days could significantly improve economic performance.

There already are a number of financial, investment and business models that offer different options for SPIS users to overcome potential funding gaps. These include community-based investment and shared liability models, Energy Service Companies (ESCO), micro-leasing and rental services. If there is social cohesion, using SPIS as group-based systems can facilitate access to finance to cover the initial capital investment, especially for poor farmers. It allows group members to share costs and risks, to benefit from the economization of input purchases and marketing expenses as well as to foster knowledge sharing (Ould-Amroche et al. 2010, Burney et al. 2009).

Economic viability and attractiveness to farmers is often compromised by subsidies for liquid fuels or grid electricity (Ould-Amroche 2010). In such cases a reform of subsidy policies could create the needed incentives for the adoption of SPIS. Reducing subsidies, however, bears the risk to affect the poorest farm households most, hence political will and risk-taking for such reforms is generally low.

Further challenges lie in the lack of skilled personnel for the design, installation and maintenance of SPIS and the lack of codes and standards. Promotion of SPIS should therefore comprise support to the development capacities and business opportunities in the supply chains and a sound legal framework.

Where can SPIS be practiced?

Technically speaking, SPIS can be practiced in any location where the following requirements are fulfilled:

- Sufficient solar irradiation, i.e. solar power received per unit area of the land surface;
- Land availability: sufficient unshaded land to support the PV panels and accommodate water infrastructure such as storage tanks;
- Water availability and legal permit/license to abstract water: sufficient water to satisfy the pre-determined irrigation water requirement of the crop(s);
- Appropriate water quality: e.g. sufficiently low levels of salinity or heavy metal concentrations.

The level of solar irradiation is strongly location-specific and depends on geographic latitude and clearness of the sky. The higher the irradiation, the smaller the required area of PV panels and for supporting land surface. PV panels constitute a main share of the total cost for SPIS. Therefore, solar insolation has a strong effect on the costs of SPIS and is a factor influencing economic rather than technical feasibility as sufficiently large PV panels can provide electricity even at low levels of irradiation (Kelley et al. 2010).

Further location-specific parameters that influence the efficiency and economics of SPIS are air temperature (optimum performance of PV panels around 28°C average with a decrease in efficiency of 0.45 percent for every degree above optimum temperature as rule of thumb) and the depth of the water source relative to the altitude where the water is utilized (pumping head; typically up to 70 m, but greater heads are technically feasible). The energy requirement for pumping – and hence the size and cost of the PV panels – increases with the pumping head. Other factors that determine the selection and sizing of the pump – and hence, costs – include size of irrigated area, topography, cropping systems, design of irrigation system and method.

SPIS and the sustainable use of water resources

It is important to note that SPIS bears the risk of fostering over-exploitation of water resources, if not adequately regulated. Once SPIS is installed, there is no cost per unit of power and, thus, no financial incentive for farmers to save on fuel/electricity for water pumping. Rather, there often is a financial incentive to intensify or expand production in order to pay off loans that were needed for the purchase of the SPI system. Thus, as SPIS might encourage improved production and increased food security, this would inadvertently lead to an increase in water consumption.

Overall, this can lead to wasteful water use, over-abstraction of groundwater, and low field application efficiency (Shah and Kishore 2012, FAO 2017). In some cases, farmers were selling water to their neighbours at a profit, increasing the overall water withdrawals. It is therefore crucial to complement SPIS technology with sustainable management of water and land resources supported by sound regulations for water abstraction and water use (e.g. licensing of drilling and water abstraction; mandatory installation of metering) and their consistent monitoring, enforcement and sanctioning.

Closas and Rap (2017) found that feasibility studies for SPIS commonly focus on technical and economic aspects, but lack an assessment of the availability of and impact on water resources. An unforeseen drop of groundwater levels, however, may also have negative impacts on the profitability of a SPIS and its overall economic sustainability.

Targeted subsidies could be linked to obligatory adoption of drip irrigation which, if properly operated, can increase the water use efficiency in the irrigated system. However this does not necessarily reduce water abstraction or may even increase it as the "saved" water resources may be used to expand the irrigated area, add a cropping season, support a change in crops with different water requirements, or they may be sold to other farmers or water users (Ahmad et al., 2007; Benouniche et al., 2014).

GIZ (2016) assume a self-regulating effect on water abstraction by SPIS due to (i) the daily limited operation window set by sunshine hours, and (ii) the high investment cost that forbids over-dimensioning of pumping capacity, following principles of economic feasibility. These principles, however, apply less in an environment with subsidies for SPIS.

Another approach to incentivize self-regulation of water abstraction is by offering competitive feed-in tariffs to SPIS owners, which would make it more profitable to feed their excess electricity into the public grid than to sell water. This requires SPIS to be connected to the grid and, if not provided, involves a major investment in grid connection. First experiences from Gujarat, India, show that the success of such a model depends on many parameters which need to be carefully balanced: e.g. offering attractive feed-in tariffs that are a multiple of the subsidized unit price at which utilities provide farm power would be uneconomical (Shah et al. 2016; Bassi 2017).

Contribution to CSA pillars:

How do SPIS increase productivity, farm livelihoods and food security

The link between the introduction of SPIS and agricultural productivity, livelihoods and food security is only documented anecdotally and still needs to be better understood. Several existing experiences have demonstrated a positive impact. In general, type and degree of impact will greatly vary depending on the situation before introduction.

Farmers in Bihar, India, were able to switch from deficit to full irrigation after introduction of SPIS, resulting in improved plant health, increased crop yields and extra income from marketing the excess produce (GIZ 2013).

In Maharashtra, India, the replacement of diesel pumps by SPIS helped to improve the on-farm economic benefits. These were in part attributed to micro irrigation practices integrated with SPIS, allowing to reduce input costs, increase productivity, and generate greater income from higher yields (Honrao 2015).

In the Sudano-Sahel area of Northern Benin, SPIS (with low-pressure drip irrigation) were installed in vegetable gardens formerly watered with cans and hauled water. This allowed the women farmers to become net producers of vegetables, generate income from market sales, and substantially increase their household nutrition intake and food security (Burney et al. 2009).

The development of sound business models ensures that improvements in agricultural productivity will translate into greater income and financial sustainability (*see* Powering Agriculture Programme[1]). In Jordan, for instance, ECO Consult is supporting commercial farms to retrofit multi-span greenhouses with hydroponic technologies and photovoltaic panels to generate enough power to operate the lighting, pumping, and air moderation systems. This allows them to achieve resource use efficiency goals and to make the technology commercially attractive.

How do SPIS help adapt to and increase resilience to climate change impacts

SPIS, in particular when relying on groundwater, provide access to water that can be used to stabilize yields and avoid crop failure during drought, a condition that – due to climate change – is expected to occur more frequently and with greater intensity in many regions of the world. In this way, SPIS can improve climate resilience of farmers, even in areas that are not connected to the electricity grid or lack reliable supply of liquid fuels. The sustainability of this resilience strategy depends greatly on the sustainable management of the supporting water resources.

How do SPIS mitigate greenhouse gas emissions?

The operation of solar PV panels is free of greenhouse gas emissions. Even when taking into account the energy-intensive production and the disposal of PV panels, the emissions from generation of power from solar energy is still considerably lower as compared to the average grid electricity mix or diesel generators. Table 1 compares GHG emissions per unit power generated, expressed as grams of CO2-equivalent per kilowatt hour (g CO2-eq/kWh), as reported in different sources for solar PV, grid electricity and diesel. Although emission rates show great variability, depending on specific technology, operating environment and other assumptions, the huge climate change potential of SPIS is evident.

Table 1: GHG emissions for different power generation technologies per unit of power (g CO20-eq/kWh) and per volume of water pumped (g CO2/m3), respectively. GIZ (2016) and POST (2011) report values from full life cycle assessment, whereas values in Ould-Amrouche et al. (2010) refer exclusively to the operation of the pumps (1 kW capacity) in Algeria with pumping heads ranging between 10 and 60 m.

	Unit	Solar PV	Grid electricity	Diesel
GIZ 2016	g CO^2-eq/kWh	16-32	600	1000
POST 2011	g CO^2-eq/kWh	75-116	488-990	-
Ould-Amrouche et al. 2010	g CO^2/m^3	0	-	480-2230

For the case of India, Shah (2009) assumes potential GHG emission savings by replacing fossil fuels for powering groundwater pumping in irrigation with renewable energy sources. Groundwater pumping is mainly powered by coal-based electricity and diesel engines with estimated annual carbon emissions of 16 to 25 Mt (or 59 to 92 Mt CO2-eq) for the year 2000, i.e. 4-6% of the national total. It needs to be noted that this estimate is strongly dependent on the assumption of the average dynamic head of water lifting (in this case 20m), as power requirements for water lifting increase with dynamic head. Therefore, Shah proposes systematic groundwater recharge for maintenance of shallow groundwater levels as an important GHG mitigation strategy for the Indian groundwater economy. This strategy can also contribute to a reduction of the required installed power for SPIS and, thus, to a reduction of cost.

Costs and funding for SPIS

The cost of SPIS is very context specific and can greatly vary depending on several factors:

- The required solar PV capacity, which in turn depends on the required flow rate of water and the pumping head;
- Import taxes for solar PV and associated equipment;
- Requirement and dimensions of water storage facilities or battery storage;
- Requirement of water filtration or fertigation equipment.

Lazard (2014, in Closas and Rap 2017) estimate the capital cost of photovoltaic panels at 2500-3000 USD/kW, compared 500-800 USD/kW for diesel engines for conditions in the United States of America. This clearly shows the higher initial investment required for SPIS when compared to conventional power options.

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[1] https://poweringag.org/

However, considered over the full life cycle of an irrigation system, several studies that compared solar PV-powered with conventional systems, found SPIS to be an economically viable and profitable alternative, in particular for applications with low installed capacity and low pumping heads, and where the water demand pattern and dimensioning of equipment are adequately estimated (Ould-Amrouche et al. 2010, Roy et al. 2015, Cuellar Bolanños et al. 2014, Odeh et al. 2006). Decreasing prices for PV panels and increasing oil prices may increase cost-effectiveness of SPIS in the future.

Despite the economic viability in many contexts, the high initial investment cost is still limiting the adoption of SPIS, especially for poor and marginalized smallholder farmers. The promotion of the technology therefore widely relies on subsidies, although even subsidies often fail to reach the poorest farmers due to requirements such as land ownership, partial coverage of cost through a loan, or simply due to illiteracy. Other financing options, such as group-based liability schemes, micro-loans and rental services could be an alternative to subsidies and should be further studied.

Metrics for CSA performance of SPIS

Productivity, livelihoods and food security: In terms of productivity, the average long-term yield is the simplest measure of system performance. Livelihood improvements can be captured by net income from crop production, which reflects reduced cost of pump operation and maintenance, intensification and diversification towards other higher-value crops. Food security can be measured by several household-level indicators such as per capita daily food consumption expenditure and daily food intake for specific food types relative to recommended daily allowances (RDA) (cf. Burney et al. 2009).

Resilience and adaptation: The mean and variance time series of crop yield data, that cover also years with weather extremes, can provide an estimate of the impact of SPIS on yield stability under challenging climatic conditions compared to similar production systems without irrigation systems in place.

GHG emission reduction: When comparing SPIS installations to alternative irrigation options, the GHG emissions (g CO^2-equivalent) are an appropriate metric to measure emission savings. GHG emission can refer to unit of power generated (per kWh), water volume pumped (per m^3), equivalent hydraulic energy (i.e. the product of water flow, m^3, and pumping head, m: per m^4), or hectare of irrigated area (per ha). Ideally the emission value reflects the full life cycle and not just the operation of the pumping and irrigation systems.

Figure 1. Panels and poly houses
Copyright: FAO/ Lucie Pluschke near Jaipur, India

Interaction with other CSA practices

The Compendium on Climate-Smart Irrigation (forthcoming; URL) provides a broader picture of irrigation and climate change, including sustainability aspects, also relevant to SPIS.

SPIS can be combined with climate-smart soil fertility and nutrient management practices such as site-specific nutrient management (SSNM) and integrated soil fertility management (ISFM).

Case study

The example of a farm west of Jaipur in Rajasthan, India, is illustrative of the many advantages and challenges that come with SPIS. The owner of this farm, however, defied the odds and in seven years managed to turn his small family farm into a flourishing agri-business with forty employees and a manifold increase in income from around 250 000 rupees (INR; around USD 3900) in 2010 to over INR 10 million (USD 157 000) in 2016, leaving him with a profit of INR 5 million (USD 78 500).

The changes began with his decision to transition to conservation agriculture and to follow a holistic approach to water, soil, nutrient, and energy management.

Around the same time, the federal and state governments jointly launched a subsidy scheme to promote SPIS. Supported by this scheme, the farmer installed a total of 82 panels and four Alternating Current (AC) pumps with a total capacity of 16 Horsepower (HP) (Figures 1 and 2). At the time, 96 percent of the capital cost was covered by the subsidy scheme. The farmer has since installed more panels, financed through a loan that the bank was willing to give him now that he had collateral. Training and regular servicing is available through the supplier of the SPI system.

What makes the introduction of SPIS so remarkable, however, is that it was accompanied with a systematic conversion of the farm from traditional field crops to horticulture and some livestock. These crops – for example, cucumbers, broccoli, pomegranate and chilli – are of greater quality and higher value, which resulted in a 25 percent increase in income according to the farmer himself. Two poly houses were installed; the fogger and cooling system are powered through solar energy, otherwise the costs would be too high. The electricity produced on-farm is also used for other electrical appliances.

Moreover, the farmer shifted from flood irrigation to sprinkler irrigation in poly houses and drip irrigation for open field crops. He built several ponds for rainwater harvesting (Figure 3). This allows him greater flexibility in how he uses water to cultivate his now 30 000 m^3 farm. Groundwater is of poor quality in the area. He therefore filters and uses it in conjunction with the rainwater stored in the ponds. During dry season, being able to pump groundwater becomes essential. Finally, the farmer noted an improvement of groundwater quality – and on-farm expenditures since he stopped using chemical fertilisers and pesticides.

Figure 3. Farmer with 5 HP pump
Copyright: FAO/ Lucie Pluschke near Jaipur, India

Figure 2. Ponds for rainwater harvesting.
They are also being for the conjunctive use of rainwater and groundwater.
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The introduction of the solar pumps was successful in this case, because the farmer had a clear idea of how he wanted to use the energy (pumping, cooling of poly houses) and because he benefitted from the support structures provided by the state government (subsidies, contracts with suppliers to continue servicing the system for five years, training). The SPI system was designed for its purpose and cleverly integrated in the on-farm water and soil management structures. Most of all, however, it was the passion and commitment of the farmer himself to make these fundamental changes on his farm.

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PRACTICE BRIEFS ON CSA

The Practice Briefs intend to provide practical operational information on climate-smart agricultural practices.

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