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Solar energy farming as a development innovation for vulnerable water basins

Mohammad Al-Saidi and Nisreen Lahham

ABSTRACT
In vulnerable water basins, unregulated access to solar energy and groundwater can threaten water security through increased abstractions. Public and development agencies are therefore exploring options to provide farmers with additional income from solar farming while protecting groundwater resources. Solar energy farming is combined with attractive purchase guarantees in order to encourage farmers to efficiently use solar energy on-farm and sell the energy excess. This article evaluates a project from the Azraq Basin in Jordan, and presents similar international experiences, particularly from India. It assesses solar energy farming as an innovation from a water-energy-food nexus perspective.

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Introduction

Energy–land integration is increasing in developed as well as developing countries. Societal challenges such as climate change impacts, the need to increase clean energy and reduce emissions, as well as rapid population and economic growth have caused additional demands for food, water, and energy. The overall rise of renewable energies (wind, solar, geothermal, biomass, hydropower) and their emerging potential use for agriculture are geared towards addressing these challenges (Chel and Kaushik 2011; Xue 2017). At the same time, the comparative advantages of renewables in agriculture and public policies to improve water, energy or food securities increase the integration between energy and land use (IRENA 2015).

Global accords such as the 2015 Paris Agreement along with the need to decarbonise economies and reduce global CO_2 emissions have pushed the growth of renewable energies. These sources are replacing or augmenting current energy sources and powering key economic sectors in developing countries. In India, for example, renewable electricity capacity will double from 2016 to 2022. Solar photovoltaic (PV) and wind energy already represent 90% of capacity growth in India due to decreased costs, while renewables are showing record-breaking growth each year in other countries in both the northern and southern hemispheres (IEA 2017). In Jordan, for example, according to the National Energy Strategy Plan, renewable energy is anticipated to reach 10% of the total energy supply mix by 2020 (Ministry of Environment 2017). The water sector is one of the major energy consumers, with 15% of total energy demands in Jordan used for water pumping. The sector is therefore targeted for renewables use and increasing energy efficiency (Ministry of Water and Irrigation 2016a). Sectors such as agriculture and water will benefit from renewable energies, as they can replace current energy sources and make relatively cheap energy available for various uses in agriculture, such as water heating, water abstraction, crop drying, grinding of grains, greenhouse heating, and lighting of facilities (Chel and Kaushik 2011).

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The favourable economics of renewables such as solar energy will allow for an increased, bottom-up adoption by farmers in the future. In particular, if fossil fuel subsidies are not present, farmers recognise the comparative advantages over fossil fuels in the long term (e.g. when the fixed costs are distributed over 10–20 years). The advantages of solar energy use include the low running or variable costs, its modular nature, relative reliability or endurance, and the avoidance of emissions, pollution or soil contamination from fossil fuels. Two important factors are expected to increase the adoption of solar farming in agriculture. The first is the fall of the module prices of PV systems. For example, in the United States alone, price decreases are expected to accelerate by as much as 75% by 2020 in comparison to 2010 (Goodrich, James, and Woodhouse 2012). Globally, in the last 30 years, the cost of PV declined by almost one fifth each time the cumulative installed capacity increased twofold (Cengiz and Mamis 2015). The second factor is the phasing out of energy subsidies for fossil fuels, thus accelerating the use of renewable energies further.

Public programmes and donor funds are steering the transition towards renewables use in agriculture. In developed countries, an important reason lies in the reduction of the carbon footprint by achieving renewable energy targets (Nelson, Gambhir, and Ekins-Daukes 2014). Here, the debates focus on the co-location of renewables with agriculture and minimising the trade-offs between energy production and the loss of land productivity. In order to do this, one can reduce the area of the land required for large-scale renewable energy projects, while allowing and financially supporting land use for grazing, livestock, and selected crops (dual systems). This land–climate–energy nexus is a key priority in developed countries (Dale, Efroymson, and Kline 2011). In developing countries, the focus might be more on the water–energy–food–livelihood nexus. Promoting the wide range of solar energy farming (SEF) applications is in a broader sense associated with different specific aims, as for example improving resilience of farmers to price and market volatilities, empowering farmers, improving yield, providing additional income and, potentially, helping to save vulnerable water resources. On the other hand, it can weaken the agricultural sector, if the produced energy is not used on farms.

This paper has two aims. First, it evaluates the SEF experience in the Azraq basin in Jordan. Second, it analyses experiences from other developing countries in order to assess their applicability for future SEF projects in Jordan, or other similar contexts. In doing this, the study highlights the Azraq case and compares it to projects particularly in India, a country exhibiting many innovative SEF projects and a long trajectory with solar energy use in agriculture. The presented projects share a common objective of improving livelihoods and farmers' income, and offering the sale of solar power as an alternative income. The paper is based on a comprehensive project evaluation and policy advice in 2017–18 for the German donor agency Gesellschaft für Internationale Zusammenarbeit (GIZ) on the SEF project in Jordan. The paper uses a water-energy-food nexus perspective in evaluating the SEF experiences, with the nexus understood as an integrative approach linking the three sectors (Al-Saidi and Elagib 2017) or highlighting one cross-cutting and cross-sectoral issue, e.g. the analysis of renewable energies within the nexus (IRENA 2015). The paper uses qualitative methods such as the study of the Azraq project documentations, consultants' reports, surveys and interviews. Most of these data were produced during the project lifetime and were provided to the authors by the GIZ, while two complementary expert interviews (a consultant and a public official from Jordan) were also conducted in 2018.

The paper largely uses secondary literature and comparative methods to analyse the challenges of solar energy farming in India with short references to other countries. India is chosen as a very prominent example of SEF applications. It is also relevant for our case study in Jordan since it exhibits the common challenge of protecting groundwater resources while improving income opportunities of poor farmers. At the same time, important insights can be gained for the relatively new experience with SEF in Jordan by elaborating on the old legacies and recent innovations in combining solar energy production and farming activities in India. The paper uses the analysis of these international experiences to conceptualise the design of SEF projects, thus offering practical and original policy recommendations on the implementation of SEF in future projects.

Solarisation of farms – applications, opportunities and pitfalls

The use of solar energy in farms can take different forms. Here, we use the term "solar energy farming" (SEF) to generally describe agricultural–solar (sometimes called agri-voltaic) utilisation systems where used arable land is either enhanced with, or converted to, solar energy farming. However, this term is not precise since "solar farming" can be used in relation to various forms of ownership, land and sea use types, and also for different purposes. Table 1 gives an overview of applications that can fall under this term. This article focuses on multi-purpose SEF applications with the Power Purchase Agreement (PPA) option or the potential for such an option. Farmers are offered an alternative income opportunity and encouraged to rationalise energy use, and reduce water pumping or even abandon some agricultural activities. In such cases, improving water use efficiency or saving water can be achieved alongside increasing use of renewables. This is particularly important for arid regions or regions with water scarcity.

Solarising farms has an important contribution to reducing the energy subsidy burden on national governments. The Middle East and North African (MENA) region harbours almost half of global pre-tax energy subsidies, and many MENA countries have started to reduce these market-distorting subsidies (Verme and Araar 2017). In the agricultural sector, the use of subsidised fossil fuels is prevalent. The decrease of PV costs, increase of fossil-fuel prices, and provision of incentives for renewables (e.g. feed-in tariffs, tax breaks, and subsidies) are expected to increase the rate of return for options such as SEF. For example, according to KPMG (2014), current economics show an internal rate of return for replacing diesel pumps with solar pumps of around 10–19%, depending on whether additional benefits such as increased crop yields are achieved.

Whether the use of SEF will be advantageous for water use is dependent on many factors. First, solar applications offer important comparative advantages from a lifecycle perspective. IRENA (2015) provides an overview of water requirements of different energy production systems (renewables and fossil) based on a full lifecycle approach (extraction, processing, transformation etc.). Solar and wind energy are among the most water-efficient production systems from a "litres per MWh" perspective and from expected water savings if water withdrawals and consumption of water-intensive fossil fuels were replaced with solar or wind energy. Using solar power can help save water, especially in Arab countries, which largely rely on power from oil and gas. Second, depending on the specific application and institutional context, using solar energy can increase on-farm water usage. In any SEF application, maintaining solar panels requires regular dust cleaning using water, which could vary significantly in different environments from fortnightly to daily (Mani and Pillai 2010). In Jodhpur, India, some PV panels are cleaned four times a month during the summer season and twice during winter, each time consuming 20,000 litres for each 0.5 MW block (Santra et al. 2017).

Table 1. Categories of applications associated with solar energy farming.

Category of SEF applications	Description and examples
Based on end purpose	
Stand-alone systems	Large utility-scale installations (so-called solar farms); no combination with agricultural production; rents for land owners.
Combined systems	Hybrid systems of agricultural land use and solar energy production on the same land unit; land used for low-intensity purposes such as conserving biodiversity, protecting land from erosion, or providing grazing for livestock; high-intensity use possible through changing the configuration of solar panels to allow for crop production underneath them.
Systems for agricultural modernisation	Incorporation of renewable energies to modernise agriculture; e.g. programmes supporting farmers in deploying solar pumps or solar-powered irrigation systems (SPISs).
Based on institutional set-up	
With a Power Purchase Agreement (PPA)	Solar energy use on farms with the option to sell part or all of produced energy through an agreement to buy energy according to a certain Feed-In-Tariff (FIT); farmers can convert their farms and become solar entrepreneurs, giving up agricultural livelihoods and selling all of their produced solar power.
Without a PPA	Use of produced energy entirely on farms for agricultural modernisation or other purposes.

However, there are more efficient cleaning systems that better suit arid Arab countries that require very little or no water input (He, Zhou, and Li 2011). Overall, the water requirements for cleaning should be analysed in the specific environment and compared to the potential impact of SEF on irrigation water use, in cases where SEF is combined with SPISs or solar pumps. The impact of SPISs on water-use efficiency is controversial and, as for other irrigation practices, largely depends on the technology deployed and institutional arrangements in place. On the one hand, SPISs have zero operational costs and therefore do not encourage water conservation (Kishore, Shah, and Tewari 2014). On the other, the operation of SPISs is restricted to sunshine periods while these systems usually pump fewer dynamic heads than diesel or grid systems. For these reasons, one would expect water abstractions to be lower than with diesel pumps, for example.

However, as the case of SPISs in India shows, high state subsidies and inadequate farmers' capacities can result in overexploitation of groundwater resources as a consequence of the dissemination of oversized (larger capacities than needed) systems and increased access to solar energy in agriculture (Shah et al. 2016; Shim 2017). In order to alleviate these problems, recent projects have combined the provision of solar technology with efficient irrigation technologies and conditions for irrigation scheduling and conservation. Furthermore, SEF with PPAs is increasing and can be designed to improve participation incentives, financing, enforcement and water use reductions. Table 2 provides on overview of some prominent SEF experiences from different countries/regions.

Synergies in the water-energy-food nexus through solar energy farming

In developing countries with high scarcity of water and arable land, farmers are encouraged to use solar energy and increasingly provided with the valuable ability of grid connection and selling excess produced energy at a subsidised price. In such cases, SEF with a PPA creates an opportunity cost of inefficient or wasteful use of solar energy. Alternatively, energy surplus can be directed towards other productive on-farm uses, such as heating, chilling, drying, grinding, and distribution (Chel and Kaushik 2011). As a result, energy use can reduce farming activities or increase water-use efficiency in vulnerable regions. Even if water availability is not an issue, SEF can target food and energy securities as well as development goals. For example, solar energy can reduce the carbon footprint of the energy sector. The food sector is an important electricity consumer, accounting for approximately 30% of global energy consumption (FAO 2011). There are many SEF applications that target food production. For example, solar greenhouses and solar-based aquaculture can be especially valuable in cold or temperate environments for winter food production, while excess energy can be sold (Mussard 2017). In China, photovoltaic energy is being used for agricultural greenhouses, in fisheries for breeding installations, for wastewater purification, in water pumping, and for improving rural electrification (Xue 2017). If solar energy targets food security or water use efficiency, it is important to establish links to extension services, water user associations, or similar institutions for improving farmers' capacities and representation. This can be achieved through changes in cropping patterns or timings, and farmers' education on sustainable irrigation practices.

There are also cases where SEF with grid connections and a PPA are not practical or economical. For example, the agricultural sector can have small energy demands or small-scale, unproductive and scattered farms. Here, off-grid SEF solutions might be more suitable, as the costs of connecting these farms or many small grids to the network are high. It is vital that SEF considers electrification plans and energy conditions at local, regional, and national levels, as this offers possibilities to rethink optimal designs. For example, instead of feeding it into the grid, the solar energy can be utilised locally for productive use and value-added on site, desalination, or wastewater treatment. Here, solar energy can provide alternative water sources to be sold to other farmers or used for recharging aquifers.

SEF can also be embedded within larger groundwater management strategies. Groundwater management plans are cross-sectoral, often negotiated strategies that stipulate a wide range of future measures. SEF can be linked to existing plans, or be conditional for the development of such

Table 2. Examples of solar energy farming experiences.

Country/region	Main motivation/objective	Deployed technology	Challenges	Some solutions
Solar energy farming with a power purchase agreement				
India	Improving farmers' livelihoods	High subsidisation of solar pumping systems; new projects offer a FIT tariff based on net-metering	Increased groundwater abstractions	Linking solar farming subsidies to water harvesting and efficient irrigation; experimentation with remote monitoring; purchase guarantees for surplus solar power in order to substitute agricultural use
Japan	Increasing agricultural output and food security	Dual systems that allow for sharing the same plot for solar energy and food production	Convincing famers to use land while producing solar energy	Financial incentives that make solar power in combination with agricultural production attractive; technical design for joint optimisation of solar panels and farms using concepts of solar sharing
USA (e.g. California and North Carolina)	Farmers faced with increasing energy costs and decreasing profit margins	Modernisation of farm-level electricity generation through solar energy; selling solar energy surplus	Fluctuation of solar energy prices	Modernisation of energy systems (e.g. storage components) and increasing energy-use efficiency on-farm level
Canada (e.g. Ontario)	A public effort to increase use of renewables by farmers and households	Solar micro-generation plants (10 kW and below) promoted through state programmes with good purchase tariffs	Conflictive use of land between agriculture, solar energy production and biofuels; decrease of agricultural land	Use of SEF on marginal lands; joint use of land for SEF and livestock or wild pasture
Solar energy farming without a PPA (Arab world examples)				
Egypt	Increasing agricultural productivity of desert land	Promotion of solar energy pumping systems	Negative impacts on water use	Initiatives to link solar pumping to efficient irrigation schemes
Morocco	Improving agricultural livelihoods and water-use efficiency	Subsidisation of solar pumping systems on the condition that farmers buy micro-irrigation technologies	Water use might not decrease; irrigation might expand; no effective control	Aquifer contracts should establish clear plans for groundwater protection and restoration on a voluntary basis
Pilot projects not yet implemented				
Jordan	Substitution of agricultural activities through solar power production and sale of power	Piloting an SEF plant by farmers on their agricultural land	Ensuring acceptability, stakeholder participation, and low-cost financing; no power purchase agreement	Different design options and institutional arrangements being discussed, including extending power purchase agreements to the agricultural sector

strategies. In Morocco (Souss Aquifer) and France, aquifer contracts among concerned stakeholders outline and operationalise restoration and protection measures (Closas and Villholth 2016). Furthermore, subsidies for solar installations can be set lower in water-vulnerable regions in order to encourage economic use. High subsidies can lead to farmers buying oversized SPISs, and thus increasing water use. Reforming subsidisation needs to happen alongside improved capacity building of farmers on key topics such as maintenance, cropping management and sustainable agricultural practices. In addition, smart and integrated subsidy policies for solar energy technologies help to reduce risks. In Morocco, for example, subsidised solar equipment can only be acquired if farmers purchase micro-irrigation systems for efficient use of water (Kingdom of Morocco 2014). A similar approach is proposed for India (Shah, Verma, and Durga 2014; Bassi 2016). Finally, in order to minimise the trade-off with land use, responsible land-use practices can be included. For example, grazing and landscape plans can be established in order to harmonise land and energy aspects. At the farm level, SEF needs to enhance capacities to monitor water use, such as using mobile phones connected to the SEF installation, metering and farm-level water-use efficiency plans. SEF can also incorporate measures to improve water availability, such as through developing rainwater harvesting practices or linking SEF to aquifer recharge plans.

The Azraq basin in Jordan

The Azraq basin is a natural wetland providing an important ecosystem and with historically high biodiversity (e.g. bird migration) and agricultural values. Azraq has been drying up since the 1980s, due to over-pumping of groundwater to supply urban areas such as the capital city of Amman. Shallow groundwater and surface springs disappeared. The rapid decline of ground and surface water resulted in the demise of this ecosystem, particularly in the early 1990s. Azraq has been negatively affected by desertification, drought, decline of agriculture, and the decrease of land productivity (Al Qtarneh et al. 2018). Currently, agriculture is still overusing the limited groundwater, leading to an annual deficit of 32 mcm/year, and a drop of 25 metres in the groundwater table between 1991 and 2016 (Al-Naber 2016). The impact on farmers is tangible in terms of increasing salinity and loss of livelihoods. Not all farmers, however, are small-scale or family farmers. Small farms date back to the 1970s when refugees from the Arab–Israeli war of 1967, and middle-income families, invested in farms as a livelihood or a retirement option (Al-Naber 2016). Since the 1990s, large farmers invested in olive plantations, expanded agricultural land, and hired professional managers. These farmers represent a powerful group of elites, and are not always in the possession of well licenses or legal land documentations.

In 2012, the German technical development agency GIZ developed the Azraq Basin Solar Farming SEF Pilot Project, which aimed to encourage farmers to give up some farming activities in exchange for solar farming, thus leading to reduced groundwater abstractions in these water-scarce regions. If farmers change traditional farming for solar farming, important contributions to saving fossil fuel subsidies or conserving groundwater abstractions are expected. In Jordan, 95% of energy is imported while energy subsidies accounted for 2.8% of GDP and around 9% of government spending in 2012 (Atamanov, Jellema, and Serajuddin 2015). The energy cost of the water sector is expected to increase by 50% from 2017 to 2025, leading to additional energy-subsidy expenditures. Further, 14% of the country’s energy demand is produced by water delivery (Ministry of Water and Irrigation 2016b). Renewable energies are scheduled to increase to 10% of total power supply by 2020, and 10% for the water subsector by 2025 (Ministry of Water and Irrigation 2016a).

Jordan has one of the highest rates of water scarcity in the world. Currently, the annual water deficit is expected to reach 26% in 2025, or 6% with the opening of the Red Sea–Dead Sea Project (Ministry of Irrigation 2016b). Although six out of the 12 major groundwater basins are over-extracted, groundwater still contributes to about 61% of total water supply, while 160 million cubic metres out of the total 972 million for water supply are delivered by over-pumping from groundwater resources (Ministry of Irrigation 2016b). If farmers use less groundwater due to better profitability of SEF, this can save valuable water. In the best case scenaario, farmers abandon year-round irrigation of annual crops in exchange for a better income through SEF. A SEF unit on 1,000 square metres of farm space can save 1,000 cubic metres, the annual consumption of around 1,000 people (Prinz 2016).

The SEF project in Azraq was expected to improve farmers' livelihoods, particularly poor farmers. According to the technical feasibility study, depending on the financing of SEF projects, farmers can earn at least four times the annual income from agriculture (around €250 per dunum – 1,000 square metres – per year) if they dedicate their farm land to selling solar power. This assumption used a feed-in tariff of €0.13 per kWh, a 5% interest rate, and no subsidies for the fixed costs (Renac 2012). However, such calculations might change with changing food market dynamics, making the financial viability of SEF projects variable to changing crop prices. Although the 2012 Azraq project did not allow solar energy for on-farm use, future projects might choose to include this option and link it to improved monitoring and irrigation practices. In this way, SEF can lead to a higher water and land productivity, and hence higher incomes and contributions to food security strategies.

The project conducted a feasibility study and surveys among farmers in 2012, which both indicated the feasible and beneficial nature of the project. In the same year, the Renewable Energy and Energy Efficiency Law (No. 13 of 2012) allowed for selling solar energy at a benchmark price of 0.10 JD/kWh, subject to change by the ministry. However, the electricity baseline selling price of 0.10 JOD/kWh changed to 0.055 (€0.065) in 2016, lowering the potential profitability of the project.

The energy law provided three opportunities to sell solar power. However, a separate PPA was needed to realise this project as this law did not foresee farmers or individual consumers selling solar energy for profit. The project ended in December 2015 with no pilot plant. The project faced difficulties securing an agreement with the relevant authorities on power purchase and access to the grid. Famers also became less willing to implement SEF, citing multiple risks.

Outcomes and contextual challenges

The SEF in the Azraq basin in Jordan did not move forward with implementation due to several factors which extend beyond the failure to implement a pilot project. We analyse these contextual factors based on evaluation reports and detailed studies commissioned by the implementation agency. For the project's success, the technical prerequisite was that farmers are given a power purchase option. This did not materialise. However, the lessons learnt from the project reveal much about integration challenges in similar projects which are often related to the institutional environment and reality of farming in developing countries. Further, the Azraq project entailed an ambitious objective of substituting part of water-intensive and unsustainable agricultural activities with more profitable livelihoods for farmers as solar farmers. The project assumed that farmers, when provided with a better income opportunity, will convert from traditional farming to solar farming, and hence water abstractions will decrease. It did not target improvements in agriculture, irrigation, or on-farm solar energy use, nor did it involve activities related to these. The direct focus on using solar energy as a stand-alone system to reduce water use by abandoning agricultural activities represented a unique example of combining solar energy, water, and agriculture. While this idea was developed through a participatory process in the basin stakeholder forum, and was later promoted by the water ministry, together with donors, it could not catalyse enough support due to three sets of factors.

Time horizon and change risks

A key issue for reducing water use through solar energy farming is the maturity of factors to induce this change. In many cases, this change is gradual. Arguably the SEF in Azraq sought to induce an impact, which is often a long-term downstream result. This is that farmers become energy entrepreneurs, agricultural land use is reduced, and the main concern of the water sector, water abstractions, is accommodated. In doing so, the project deliberately avoided linking SEF activities with land and water use, or providing farmers with options for the use of solar energy. The long-term impact of substituting farmers' livelihoods is however difficult to achieve through a project providing technical approaches (pilot solar farms), or indicating profitability advantages (economic feasibility for farmers). This is particularly true if disincentives and risks exist in the face of such changes. For example, while land productivity and profitability decreased in the Azraq case (disincentives), attractive factors remained in agriculture, such as high energy and water subsidies as well as hidden incentives through illegal land use. Further, key pull factors in the solar farming sector were little manifested. The transaction costs of change in terms of the lack of transparent information on change requirements and processes, unattractive financing mechanisms for businesses, and unstable future profitability were arguably high. As a result, farmers were faced with risk ambiguities regarding the financial subsidisation related to the pilot project and the availability of an attractive FIT. For energy and water stakeholders involved in the project (e.g. ministries, power company, distribution company, renewable energy fund), there were also risks related to the continuation of water abstractions despite the project, and the costs associated with the grid regulation and connection, resulting in low overall support and participation, particularly from agricultural and energy stakeholders.

Suboptimal integration arrangements

Four ministries along with their specialised agencies were involved, with no clear institutionalised decision-making mechanisms. This is a fundamental issue required for facilitating cross-sectoral projects. There are ad hoc forms of cross-coordination in Jordan such as inter-ministerial working groups and committees. However, these are task-driven (e.g. development of a joint agriculture–water strategy), and lack real powers such as initiating, approving, or exempting projects. The lack of a clear instrument leads to confusion about who should take the decisions, who should lead, and based on which authority. As a result, decisions are referred to higher levels, such as ministers and cabinets. This leads to delays and often results in no decisions, as with the Azraq SEF project. Even if a decision to support a project is made at a higher level, it does not solve procedural issues. The questions of who takes implementation decisions and who acts as the lead authority are not resolved.

However, for future projects, establishing an authorised body such as a task group or a committee, to facilitate prioritised projects might be helpful. There is already a task group on water–energy issues, but its decisions are not binding. Such solutions are therefore not feasible in the long-term, as it is impractical to initiate an irregular, exceptional procedural arrangement for each project. A more sustainable solution would entail detailed regulations on coordination procedures and decision-making in issues concerning different ministries. At the same time, the novelty of this project, as well as of renewables projects in general, represented a new challenge. The institutions did not have relevant experience to build on, whether in administrating or implementing the SEF project.

Missing capacities

Farmers lack the technical and managerial knowledge to engage in renewables projects and require support in this regard. This is even more important if they need to compete with professional endeavours in highly attractive renewables markets. The public institutions also lack the capacity to monitor and administer cross-sectoral projects. The current capacities are sector-oriented and not flexible enough to be integrated into multi-issue and multi-sector projects. Lead institutions for the project require expertise in different sectoral aspects and should thus be offered training and support. This is especially true for developing project guidelines, policies, and monitoring instruments for SEF to improve groundwater quantity and quality. Intermediaries such as extension services, and private sector companies offering advice and services to farmers and farmer associations, can play a positive role in developing capacities.

The increased mobility of famers (e.g. capacity, education, and affluence) can also push farmers to pursue employment in other sectors. However, this mobility is low in the Azraq case, and has not been enhanced through capacity building or training. At the same time, projects envisioned under the renewables law were geared towards economies on large-scale applications and increasing energy efficiency. The Azraq project, oriented towards social policies such as supporting farming and reducing water overuse, did not fit within current renewable energy policies. This resulted in low support for the provision of a subsidised FIT for the Azraq SEF project.

The design of agri-voltaic projects – new insights from India

Recent projects in India demonstrate that a partial livelihood transformation can result in the short term as farmers decide to gradually supplement their income with solar farming. Often, these projects regard such transformation as an impact of an intervention linking on-farm solar energy use to a power purchase agreement. India has a history with solar pumping systems (SPSs) and solar-powered irrigation systems (SPISs) dating back to the early 1990s, which is still controversial with regard to the impacts on vulnerable water resources such as groundwater. According to Bassi (2016), SPSs policies are starting to change focus. Previously, they centred on increasing subsidisation of SPSs, cheap energy, and equitable access to groundwater. Scholars now emphasise options to directly or indirectly protect groundwater through solar systems, such as tradeable water rights, pro rata pricing systems, and SPSs with drip systems. This new focus is due to the criticism of previous projects, which led to oversized SEF installations and lacked enforcement mechanisms regarding SEF use for water abstraction.

Groundwater usage has become the main source of irrigation in India, since the deterioration of irrigation infrastructure and the increase in rural electrification led farmers to turn to groundwater (Sharma 2015). Agriculture is the major employment sector in India – around 42% of total employment in 2018 (World Bank 2018). The government therefore encourages solar power use in agriculture, providing high subsidies to the capital cost of SPSs. This is motivated by the desire to improve rural development and farmers' income, and by the fact that irrigation pumps – around 20 million, of which 9 million run on diesel – and the agricultural sector account for 22% of total electricity consumption (Agrawal and Jain 2016). In 2015–16 alone, more than 30,000 solar pumps were installed, more than the number installed in the previous 25 years (MNRE 2016). This reflects growing public investments in SPSs. Nowadays, there is increased attention from donors to developing more integrated projects linking solar energy use to agricultural productivity and water reductions. Table 3 provides an overview of projects representative of integrated SEF projects, identified during a review of recent SEF experiences in India, which highlight new directions to redesign SEF projects by linking them to water use issues.

India provides some relevant insights for the Jordanian case. First, the public commitment to solar energy in the agricultural sector is high, and part of broad strategies to promote renewables. Since 1992, solar pumps useage has been encouraged by state agencies providing subsidies of up to 90% of total costs (Shim 2017). Second, donor organisations are involved in many projects, and recently collaborated with the government on more integrated or smart approaches, and also on building the capacities of farmers. Third, the lack of awareness of farmers on SEF technologies and lack of knowledge on maintenance and irrigation practices present key obstacles for the economic and social sustainability of SEF in India (Agrawal and Jain 2016). Fourth, the government deploys a diversity of approaches in promoting solar energy in agriculture such as grid-connected pumping, solar pump mini-grids, replacement of diesel pumps with solar pumps in off-grid areas or community-based or water-as-a-service systems (MNRE 2014). Finally, the promotion of solar pumps in India was financed by high subsidies. These are criticised for several reasons such as missing links to sustainable practices in groundwater (Bassi 2016, 2018); their pro-rata basis (Kishore, Shah, and Tewari 2014; Shah et al. 2016) or the lack of net-metering of evacuated power (Shah, Verma, and Durga 2014). There is also a debate about the cost–benefit of SPSs around small-scale plants and high infrastructure costs for connecting farms to the grid (Bassi 2018).

Table 3. Integrated solar energy farming projects in India.

Location	Main challenges addressed by project	Project highlights
State of Gujarat	High burden on power plants by agriculture (25% of grid electricity usage); groundwater depletion	A Solar Pump Irrigators' Cooperative Enterprise (SPICE) of six farmers in Dhundi village; surplus of six net-metered pumps, with a total capacity of around 56 kWp sold to the local power utility; a 25-year power purchase with the power utility at the rate of around US$0.07/kWh. IWMI-Tata programme provides a Green Energy Bonus and a Water Conservation Bonus, bringing the total feed-in tariff to $0.11/kWh.
State of Bihar	Groundwater over-abstractions	A pay-as-you-go model established as a business model of providing "water as a service"; water user associations cooperate with a private company responsible for operation and management of a solar pumping system; associations charging government-fixed irrigation fees and optimising irrigation.
Karnataka State	Groundwater depletion	Surya Raitha public programme promoting grid-connected solar irrigation PV pumps on a net metering basis through a 90% cost subsidy and a feed-in tariff of around US$0.15/kWh for non-subsidised plants, and US$0.11/kWh for subsidised ones; support of 10,000 pumps; government providing subsidies for systems up to 10 HP, a capacity of 10 kWp.
Rajasthan State	Highest potential for solar power in India but groundwater-vulnerable state	Programme to construct additional tanks and diggis to counteract negative impacts on groundwater recharge; linking solar pumps and water harvesting; subsidised pumps not connected to the grid; farmers required to deploy drip-based micro-irrigation systems and farmers with a diggi are preferred.
Odisha Sate	Climate change, monsoon variability, climate extremes, groundwater availability	"Ground Water Recharge and Solar Micro Irrigation to Ensure Food Security and Enhance Resilience in Vulnerable Tribal Areas of Odisha" project under Green Climate Fund with a total investment of US$166.3 million; linking community-based rainwater harvesting measures (recharge shafts in 10,000 tanks) and improved irrigation schemes through the use of 1,000 solar pumps.
West Bengal State	Low development of irrigation capacities; climate change	US$300 million by the World Bank for the "West Bengal Accelerated Development of Minor Irrigation" project; as part of the project, hybrid solar photovoltaic systems for pumping purposes are equipped with a GPRS wireless modem, automatically transmitting data on flow and energy use.

Table 4. Technical design options for SEF projects.

Category	System design	Main contributions	Potential problem areas
Level of integration	Integrated project design, e.g. solar pumping with drip irrigation or/and water harvesting	Increase in water-use efficiency. Possible decrease in water use. Increased aquifer recharge.	Difficulty in controlling the implementation. Possible decrease in irrigation area.
	Dual solar–agricultural systems (solar sharing)	Maintaining productive agricultural use of land. Potential reduction of irrigation needs due to higher soil moisture underneath the panels.	Site-specificity of feasibility and optimal design. No water reductions or potentially higher water use.
	Agricultural modernisation	Improved access for irrigation water. Improved land productivity.	Possible water-use increases. Missing incentives for water-use efficiency.
Grid connectedness	Mini-grid	Lower connection and operation costs than connecting smaller plants or pumps. Design flexibility in relation to national grid and local supply. Possible separation of irrigation solar power supplies from residential ones.	Potentially unsuitable for small countries and availability of national grid. Not optimal if net-metering of all sub-systems is required. Little control over individual solar production if the power produced is evacuated to one single point.
	Grid-connected selected SEF plants	Connection and operation costs less than net-metering. Better control at the plant plants. Possibly less costly than mini-grids.	Plants needs to be large enough to justify connection costs. Operation and ownership of plants needs to be clarified.
	Net-metering of pumps and plants at farm level	Individual control over solar production and consumption. Higher incentives for water and energy saving.	High grid connection and operation costs. High costs for ensuring grid stability and power quality.

Table 5. Policy design options for SEF projects.

Category	System design	Main contributions	Potential problem areas
Level of subsidisation/ public engagement	High subsidisation	Higher acceptance by farmers. Higher access, and possibly equity, in solar power development.	Adverse incentives such as purchase of oversized, water-wasteful systems. Negative technology dissemination. In case of a high FIT, possible malpractices such as meter-tampering. Cost-intensive, while subsidies might favour large farmers.
	Moderate subsidisation	Optimal balance in terms of promoting acceptance, access, and technology dissemination. Cost savings.	Small farmers might still not be able to afford to buy the SEF systems.
	No subsidisation	Increase of economic competition. No costs.	Little acceptance or affordability by farmers to adopt solar power. Possibly promoting inequities within farmers, since large farmers can better afford solar energy.
Level of regulation of water use	Pricing reforms	Pricing water based on solar energy use promotes savings. Simple to administer and effective.	Politically difficult to adopt due to low acceptability. Requires effective metering and enforcement.
	Regulatory command and control	Low administration cost in compliant cases. Easy to adopt.	Requires punishments, monitoring instruments and enforcement mechanisms.
	Monitoring and information-based	Provide simple incentives for voluntary compliance. Possible improvements on water-use efficiency.	Less effective than economic and regulatory instruments. Potential high costs for installing monitoring systems.
Level of cooperation among farmers	Community-based	Pooling capacities, improving honesty and peer control. Dissemination of economic benefits.	Capture by strong or influential members. Difficulty finding homogenous groups or communities.
	Water as a service	Improving solar plants' operations and profitability as well as irrigation practices. No running costs for farmers.	Forgone benefits for farmers from not being owners. Might mean a water price increase, leading to non-acceptance by farmers.
	Individual ownership	Provide most incentives for farmers.	Difficult to monitor and enforce in cases of malpractice.
Support for capacity building	Public services	Provide publicly funded capacity building services.	Require significant public funding and also engagement from civil society and other donors.
	Private intermediaries	Offer integrated private services for SEF and transition to SEF.	Do not emerge if there is no attractive PPA for SEF, since farmers cannot pay for the services later on.

Discussion of SEF design

The experiences in India differ from the Azraq case as they promote integrated SEF projects focusing on agricultural modernisation, in contrast to the standalone idea in Azraq of alternative livelihoods. Further, they provide diverse approaches based on gradual change that can accommodate farmers' realities and link solar energy to water and land use. At the same time, the strong participation of the energy sector in India is an important lesson for countries such as Jordan. Although not all projects aim to include sales of surplus power, including a PPA on a net-metering base for solar pumps is possible in the future. Further, recent Indian projects focus on small-scale farmers using approaches such as pay-as-you-go and water as a service. These could be appropriate for poor farmers in Jordan who cannot afford solar-powered applications and who can profit using the professional services of intermediaries.

The Indian case also provides useful insights into institutional and regulatory issues. First, it is important to address SEF as a part of renewables legislation and policies, but with specific programmes and strong public commitment. This ensures funds, commitment, and collaboration of the agricultural sector. Newer projects at state level, in collaboration with donors, tap into these programmes to develop SEF projects with a PPA with similar orientation to the Azraq project, namely reducing water use in agriculture. Second, governmental banks supervise the subsidisation programmes while, in recent schemes, so-called "system integrators" buy the SEF applications and provide integrated solutions (system, installations, maintenance) to farmers through designated dealers. Farmers can choose the dealers, request a subsidised loan, and then receive the SEF solution in a few steps (Shim 2017). This enhances the availability of SEF applications and helps farmers who lack the understanding of SEF applications and their maintenance.

The diverse experiences of SEF reflect the multiple and sometimes conflicting goals of SEF projects. For example, easy access to solar energy often promotes inefficient use of water and energy. In addition, net-metering of small solar pump stations can be more costly than metering water use at agro-wells. Such examples highlight the inherent trade-offs in designing SEF projects, or any WEF nexus project. Tables 4 and 5 summarise key technological and institutional design options proposed for solar energy farming projects. These represent critical issues based on international experiences and are indicative of current directions in SEF project design.

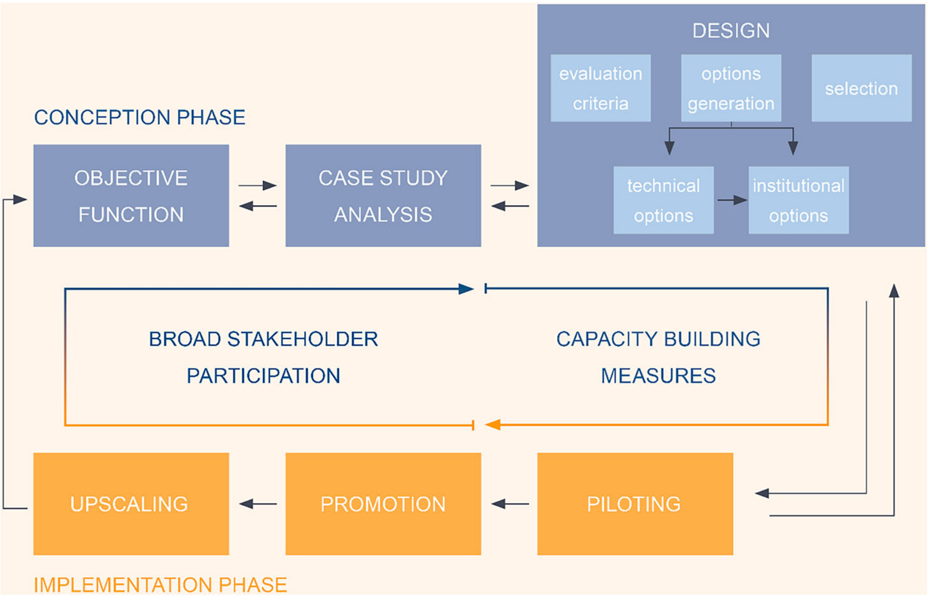

Figure 1. Cycle of SEF conception and implementation.

In order to provide further recommendations for SEF project design, it is important to look at the project development process itself. For SEF projects to succeed, the key to minimising trade-offs and increasing synergies lies in optimal project design and implementation. Figure 1 shows a cycle proposed by the authors for the conception (preparation and development) and implementation of SEF projects. Such a cycle could avoid the pitfalls of the Azraq project, but also applies for future SEF projects. In this cycle, it is important to determine the objective function based on the local context. The design process includes determining evaluation criteria based on the objective function as well as evaluating and selecting options highlighted earlier. Finally, it is important to include capacity building and participatory arrangements in the different phases of SEF project design.

Conclusions

The use of solar energy on farmland shows a diversity of approaches that address objectives such as renewables dissemination, water use efficiency or agricultural productivity. The SEF experiences from Jordan and India seek to partially or completely substitute agricultural production with solar farming activities, in an effort to reduce water abstractions. However, a successful livelihood change is often gradual, while change risks and the capacities of farmers need to be addressed in any change process. In addition, farmers can voluntarily shift to solar farming in pursuit of better profits as a result of a high FIT. However, these decisions seem unstable and reversible upon changes of the FIT. Overall, a long-term livelihood transformation requires a range of push and pull factors that are very difficult to influence through single projects or analytically address in full. The Indian experience is different from the Azraq project in three different aspects: project legacies, leadership and integration. The Indian case is older with new agricultural modernisation projects increasingly incorporating power purchase options and linking solar energy use to water and land sustainability issues. Further, the energy sector led SEF projects, with strong participation by agricultural actors, and recently water sector stakeholders. Finally, the projects are more integrated in providing more direct links between agricultural activities, water use, and solar energy.

Solar energy in agriculture presents challenges for water use, but also offers opportunities for water, energy and food securities if attractively designed, such as through the use of a FIT. A key determinant of the success of SEF is context-specificity and the systematisation of project design. The location determines the resource potential and current resource uses, and hence the primary objective of the SEF application. The SEF project design determines the anticipated changes in resource-use patterns. Project design needs to consider different policy and technological options while ensuring capacity building, particularly of farmers, and the involvement of key stakeholders.

For the Azraq project, some lessons can be learnt in order to improve the outcomes of implementing this promising idea. More integrated and smart projects (linking solar energy to water use, agricultural practices, recharge management) can reduce risk ambiguities and improve participation. Particularly for the piloting phase, some level of subsidy seems necessary, although these should be moderate. For this, it is important to incorporate the economic and welfare aspects in renewables policies, such as energy subsidy savings, welfare benefits from water reductions or improving farmers' livelihoods. Increased collaboration and convincing participation strategies are necessary to gather support from energy, agricultural, water, and environmental stakeholders. Finally, international experience shows the need for institutional and regulatory arrangements. These involve a coordination mechanism among public stakeholders, clear roles and responsibilities in renewables programmes, regulations for water use or conditions for allocations, subsidies for farmers and incentives for the participation of intermediary organisations such as extension services or civil society supporting farmers.

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