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Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations

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ABSTRACT

The increasing demand for solar-powered irrigation systems in agriculture has spurred a race for projects as it potentially offers a cost-effective and sustainable energy solution to off-grid farmers while helping food production and sustaining livelihoods. As a result, countries such as Morocco and Yemen have been promoting this technology for farmers and national plans with variable finance and subsidy schemes like in India have been put forward. By focusing on the application of solar photovoltaic (PV) pumping systems in groundwater-fed agriculture, this paper highlights the need to further study the impacts, opportunities and limitations of this technology within the Water-Energy-Food (WEF) nexus. It shows how most policies and projects promoting solar-based groundwater pumping for irrigation through subsidies and other incentives overlook the real financial and economic costs of this solution as well as the availability of water resources and the potential negative impacts on the environment caused by groundwater over-abstraction. There is a need to monitor groundwater abstraction, targeting subsidies and improving the knowledge and monitoring of resource use. Failing to address these issues could lead to further groundwater depletion, which could threaten the sustainability of this technology and dependent livelihoods in the future.

1. Introduction

Agriculture remains a major challenge to achieve overall water, energy, and food security. In order to address the need to increase water access for growing populations, produce renewable and clean energy, and feed the planet, solar-based groundwater pumping for irrigation (referred to SGPI) has been put forward as part of a sustainable energy portfolio for both developed and developing countries. The use of solar technology is expanding worldwide and since 2010 the world has seen more solar energy system capacity installed than during the previous four decades (IEA, 2014). In the Middle East and North Africa (MENA) region alone, solar photovoltaic energy production increased with 112% between 2008 and 2011 (REN21, 2013).

As a potentially cost-effective solution capable to provide off-grid electricity with solar radiation, one of the policy aims of SGPI is to increase agricultural productivity by securing access to groundwater resources for farmers. In the absence of reliable electric supply, these systems seek to provide a viable solution for agriculture as they offer operational and maintenance (O&M) advantages, increasingly low investment costs and environmentally positive trade-offs in the form of carbon free generated electricity. The use of this technology would also reduce variable costs (e.g. O&M costs) and the reliance on diesel or electricity, leading to higher profits for farmers. This solution also addresses the interconnected challenges arising from the WEF nexus by providing safe access to water and energy which in turn contributes to improving food production (Fig. 1) (FAO, 2014).

Solar pumping was already used in the 1960s and 1970s (e.g. van Campen et al., 2000; Rosenblum et al., 1978; Smith and Allison, 1978; Ward and Dunford, 1984; World Bank, 1981) but its expansion was limited to a small number of cases due to its high costs (Howes, 1982, 1984). Recently, a new set of circumstances has recently put it back on the map: 1) a general focus on renewable energies and carbon-emission offsets; 2) the need for increasing food security and improving livelihoods; 3) a radical reduction in solar panels prices; 4) the increase in oil prices; 5) new technical and more affordable designs for small-scale irrigation systems. Experiences include the Gulf countries (Doukas et al., 2006; Sahin and Rehman, 2012), Yemen (IFC, 2014; World Bank, 2015), Egypt (Hattingh, 2013; Mahmoud and El Natherb, 2003), and Morocco (IFC, 2014; Lorentz, 2013). Other countries such as Benin

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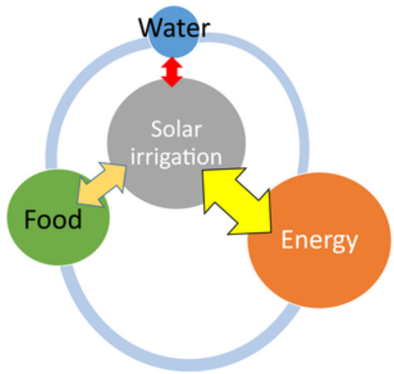

Fig. 1. The water-energy-food nexus and solar-based groundwater pumping for irrigation.

(Burney et al., 2010), India (Shah et al., 2014), Bangladesh (World Bank, 2014), and China (Yu et al., 2011) have also been testing this technology.

Against this backdrop, this paper reviews the application of solar technology with PV for groundwater pumping in irrigation and argues that in most cases where this technology is used, the financial and environmental sustainability of these projects are generally underplayed or sometimes even overlooked. As will be examined, such lack of financial and environmental sustainability can lead to ineffective state policies promoting the technology (e.g. targeted subsidies) and increased groundwater resource overdraft.

Water and energy are both necessary inputs for food production and along the supply chain, with the nexus representing a way to describe the interconnectedness with the existing global resource system (FAO, 2014). SGPI can increase food production by harnessing reliable and sustainable energy to provide timely irrigation. However, these benefits may be at risk as many technical feasibility studies on SGPI fail to appropriately evaluate available water resources and water use (dependent on solar pump extraction capacity) and the arising tradeoffs within the water-energy-food nexus (Fig. 1). For SGPI, variable costs may be lower than other energy options but in the long term total costs (including environmental sustainability of natural resource use and total capital costs) might be considerably larger. The environmental sustainability of SGPI is problematic as assessments generally assume constant groundwater and no varying natural conditions due to increased resource abstraction. Poor regulation, rule enforcement and monitoring of groundwater abstraction levels through state regulation and management may increase the risk of resource depletion from these ventures and their medium to long term sustainability.

In order to further examine these issues, the structure of this paper is as follows: the technological development and limitations of SGPI are scrutinized in the first section. The following section examines the economic and financial limits of SGPI focusing on the impacts of specific state policies such as the use subsidies, access to finance and markets for this technology. The next section addresses the environmental sustainability of SGPI and the lack of assessment and understanding of groundwater resources in most projects. The final section raises some concluding remarks and reflects on potential policy directions to be adopted vis-à-vis the necessity to improve the financial and environmental sustainability of solar-fed groundwater pumping for irrigation.

2. The development of solar-based groundwater pumping for irrigated agriculture

2.1. Solar pumping: a new technological fix

Many developing countries have large energy needs but lack financial resources to expand their electric grid rapidly enough. Aging energy generation plants and increasing population drives the demand for more energy. Solar technology seemingly provides a modular solution for users to quickly develop and independently develop private off-grid electricity-production systems.

Off-grid PV groundwater pumps for irrigation have been studied and used for over 40 years and there is nothing new about the application of this type of technology in agriculture. The technology consists mainly of solar PV panels, an engine and a pump (submersible, surface or floating, according to well characteristics and needs) connected to a well (Kelley et al., 2010; Meah et al., 2009; Van Pelt, 2007). It is only after the 1990s and 2000s that some of the necessary and enabling conditions for developing and upscaling this type of technology have been met, making it more attractive and economical for more farmers worldwide (van Campen et al., 2000). In the MENA region, governments have been encouraging the substitution of diesel pumps with solar-powered ones through credit lines (e.g. Morocco) or by directly investing in such technology in land reclamation projects (e.g. Egypt).

Solar-powered pumps have higher initial costs (the retail price of technology) compared to diesel pumps, but lower O&M costs in the long run, offering higher reliability than diesel generators. Even though capital costs can vary according to each country (for example according to capacity value, stranded costs related to distributed generation, or compliance with environmental regulations), Lazard (2014) established the range of total capital costs for Solar PV between 2500 USD and 3000 USD per kW and for diesel between 500 and 800 USD per kW. However, recent drops in production costs of solar panel technology 30–60% in 10 years, with a historical global drop from around \$76/W in 1977 to \$0.30/W in 2015), coupled with increasing oil prices have made this type of technology more attractive to decision-makers, technicians, and users (Bloomberg, 2016; Nederstigt and Bom, 2014).

2.2. Technological limitations

A particular set of conditions enhances the technical efficiency of SGPI. Solar radiation and light intensity has to be constant and over a certain threshold. Solar pumps can also be less efficient than diesel pumps as sun radiation variations and exposure can drastically decrease the efficiency of these systems (Ahmad and Ali, 2011). The outputs of solar systems also depend on system design, accurate site and demand data with appropriate measurements. These have to be accurate in order to understand water demand from the irrigation system as well as groundwater availability, something that cannot always be done (for lack of data, studies, or funds to carry them out). Additionally, it has been reported that solar-powered pumps are more suitable for low and medium head water pumping and where grid-connected systems cannot rely on electricity (Gopal et al., 2013), thus making it difficult in some cases to scale up the technology.

The productivity of these systems can be further decreased by the following factors affecting the performance of these systems: ambient temperature, poor maintenance of the panels (dust accumulation and improper cleaning), wind velocity and relative air humidity (ibid.). Solar energy is also not available on demand and cannot cater for fluctuating water demands, unless the daily variation in solar power generation is stored in batteries or lifted water is kept in a storage reservoir, thus requiring further investment capital (Abu-Aligah, 2011). A lack of data makes it difficult, according to Nederstigt and Bom (2014), to estimate pump lifetime and thus annual costs of these systems. No post-implementation studies have been found in order to compare with ex ante feasibility studies and contrast assumptions with results and system performance.

3. The economic and financial limits of solar-based groundwater pumping

3.1. Subsidies and the real cost of solar pumping

One of the reasons why, across the world, solar pumping has been adopted until now is because of direct and indirect state subsidies for capital investment. This can be considered an active policy decision as energy deficit builds up and countries move towards cleaner energy sources to reduce CO_2 emissions. The demand for this technology is also linked to electricity availability, power supply conditions, and the initial price of other sources of energy used for irrigation. Even though solar pumps cost more to install than diesel or electric pumps (as a lump-sum linked to the initial purchase and installation), studies seem to agree that the cost reduction varies depending on the initial investment required, and the feasibility to access and import this type of technology overcoming trade and custom barriers.

Having said that, if power supply conditions are acceptable and electricity supply is free for the consumer, the incentives for farmers to switch to solar-based pumps are null (Shah and Kishore, 2012). Even though many studies have proven that over the lifetime of a pump system, solar-powered pumps are more efficient and less costly than diesel pumps, fuel subsidies can make diesel-powered pumps more economically advantageous regardless of any technical advantage provided by solar-based pumps, as seen until now in Egypt for example (Hattingh, 2013). Moreover, capital and maintenance costs are estimated in cost studies but are rarely disaggregated by individual product or component (Paulsen and Reynolds, 2010). Total costs of SGPI would add up given the need for more water, the additional pump, and the need to build a reservoir to store the pumped water during the hours of solar radiation (Hattingh, 2013).

A tangle of fiscal incentives and commercial policies promoting subsidies and state-controlled markets make the assessment of the real financial costs of this technology difficult as they fail to reflect the real price of this type of technology (Radulovic, 2005). Financial studies of solar pumping systems (e.g. Purohit, 2007; Purohit and Kandpal, 2005) found out that this type of technology represented a viable option when sufficient incentives were provided through government policies and investment (e.g. capital subsidy and low interest loans). However, many project justifications and cost comparisons carried out by different authors (e.g. Chandel et al., 2015; Kelley et al., 2010) do not take into account the sunk cost of these subsidies in the real price of the technology and the impact on the retail price on consumers. Thus, the provision of technology below cost produces market distortions and in some cases has caused losses, cutbacks, and bankruptcy for some firms (Bazilian et al., 2013).

It is expected that if subsidies or financial incentives such as soft credit lines and loans were to be lifted or reduced, the investment and net present value of SGPI could become much less attractive and potentially economically unviable for many small and medium size farmers with difficulties accessing capital. Equally, if subsidies are lifted during the life-span of the project or if groundwater is depleted, then the internal rate of return of such project could be affected thus raising concerns about the financial sustainability of the investment and increasing the prospective costs of the system in the future (Purohit and Kandpal, 2005). As an example of the latter, in Morocco, targeted subsidies for solar pumping have been put on hold due to the government's concern for the depletion of groundwater resources (Ministry of Agriculture, pers. com., 2016).

3.2. Access to finance and markets and the role of state policy

As seen in the previous section, governments have been subsidizing solar technology for irrigation in order to increase demand and develop a market for this technology. However, the initial investment needed to install and develop SGPI can be hindered by the lack of credit or capital available to some farmers. Access to such technology can also be a limiting factor, and, wherever lacking, a market to sell and buy this technology would need to be regulated, with finance and technology supply available and reduced trade barriers so that technology and replacement parts can be made easily available in local markets. Farmers can also rely on loans from the government or banks or micro-credits to finance these schemes. However, banks and credit institutions in these countries may lack the understanding of the technology required to develop adequate financial products for users.

As Radulovic (2005) showed, viable PV markets need successful entrepreneurial projects with sales and service delivery. The access to this type of technology is still limited in many countries due to a lack of local manufacturers and technical expertise. The import of solar technology via intermediaries increases its price, even more so if there are trade barriers and high import taxes. Trade barriers would have to be reformed in countries in order to make technology more available and affordable. Training of farmers and technicians to use this technology is also essential and the lack of it could constitute another limitation. The lack of technical staff in rural areas of India trained to install and repair these systems and poor supply chains for components can affect the system lifespan or delay repairs (representing an additional cost for the farmer) (Bassi, 2015). Theft of agricultural equipment is also an additional risk farmers would have to face if they installed this type of systems in remote rural areas, as this stolen technology can be re-sold.

An indirect way to help boost the market for solar pumping technology is by exempting them from import taxes applied to foreign suppliers of PV panels and modules (including components not specifically used in PV such as pumps and wirings) (IFC, 2014). Another indirect way is by creating incentives for farmers to sell the electricity generated by solar PV technology through feed-in-tariffs. This solution has been proposed in Jordan in the Azraq basin under the name of ‘solar farming’, providing price incentives for the electricity generated and sold to the grid, creating income for farmers-turned electricity producers (GIZ, 2015). The development of this scheme however faced difficulties as the government is not interested in providing solar technology for farmers for fear that they might continue over-abstracting groundwater (ibid.). In India, the introduction of solar pumping is also raising concerns due to the already existing over-abstraction of groundwater (Shah et al., 2014). In areas where electric pumps are prevalent, electricity rationing is used as a control measure to limit groundwater pumping in irrigation. With farmers going off-grid, the government would lose this potential regulatory tool.

Access to SGPI can also be limited to certain farmers and its benefits can escape small farmers like in Bangladesh, especially if they do not own the land they farm (Howes, 1984). Land tenure insecurity can detract farmers from investing and baring the initial capital costs of this technology. Financial incentives can also be restrictive and target land owners (e.g. in Rajasthan, India, were the use of subsidies for SGPI can only go to farmers owning 0.5 ha of land or more, with a water pond, and drip-irrigation) (Bassi, 2015). Larger farmers with access to credit will not be affected by limitations and will be able to develop the technology, potentially leading to increasing inequalities in access to groundwater and access to additional sources of income as it happened in the Punjab, where subsidies were provided for the wealthy (Radulovic, 2005).

4. Natural and environmental limits of solar-based groundwater pumping in irrigation

When the economic and technical justifications of SGPI are put forward in feasibility assessments, studies often fail to grasp the environmental sustainability of solar pumping arising from the needs associated with groundwater as a resource and its use. The consideration of free access to groundwater by users in these assessments, a situation which exists in many parts of the world (Giordano and Villholth, 2007), assumes the implicit idea that groundwater is available and its 'stock' is unlimited. This is due, in many cases, to a poor valuation of water abstraction rates, or optimistic assessment of hydrogeological variables and processes (Kelley et al., 2010; Yu et al., 2011). The understanding of groundwater flow dynamics often will assume linear recharge rates and a poor consideration of existing climatic and biophysical conditions. The fact that no groundwater overdraft exists prior to the development of a project – or allowed within 'tolerable levels', is an assumption used to justify the development of SGPI according to Yu et al. (2011) in China and not as a potentially limiting factor for such investment. The same research however fails to establish the degree of 'tolerability' or quantify it, endangering the environmental feasibility and future sustainability of these projects. As a result, in Jordan for example, the Ministry of Water and Irrigation is not keen to promote solar-based irrigation with farmers because of the already existing over-exploitation of resources.

Many technical and economic feasibility studies fail to acknowledge and evaluate groundwater resources both in terms of its quality and quantity over the length of a project, possibly due to lack of accurate data. This has the potential to reduce project life span if the resource is not as abundant as expected or if decreasing groundwater levels trigger the deepening of surrounding wells. The future of SGPI ventures can be at risk if groundwater pumping rates deplete aquifers faster than they are recharged. As Fedrizzi et al. (2009) point out, groundwater resource parameters such as the static and dynamic level and aquifer recharge capacity can undergo great variations depending on the geological substrata, rainfall patterns, and topography. Also, resource depletion can have an impact on aquifer yields and therefore on available groundwater, affecting crop water needs and harvests with decreases in irrigated area. The lack of understanding of specific crop water requirements can also be a limiting factor for the use of this technology with potential serious impacts on the configuration of the irrigation system and the volume of groundwater needed abstracted.

Given the heavy initial capital input, it can be assumed that when a solar pump is installed, farmers will try to maximize its use and groundwater withdrawal in order to recover the high capital costs (either by expanding their irrigated area or potentially selling water to other farmers). This could potentially lead to a 'race to the bottom' unless control and limitations are put in place. In places where enforcement of rules and abstraction controls are lacking this could contribute to the exhaustion of groundwater resources. As Shah et al. (2014) put it, the introduction of solar pumps for irrigation needs to take into consideration the fact that it is 'an energy-and-water' solution and that it can aggravate the water scarcity problem as much as it can improve the energy-access problem.

No direct mechanisms to control potential groundwater over-draft generated by SGPI are generally recommended other than the use of meters and monitoring (IRENA, 2016). However, in remote places this may not be of much use as users can lack the capacity to read the meters and potentially calculate the yield. Subsequently, additional training and knowledge has to be developed. Moreover, water meters can be subject to tampering and vandalism such as in Jordan (Chebaane et al., 2004) or corrupt local agents can benefit from bribes for new well permits such as in Syria and Jordan (Barham, 2014; de Châtel, 2014; Zeitoun et al., 2012) and poor oversight of meter readings such as in India (Aguilar, 2011).

Additionally, under the current adoption paradigm, a focus on water use efficiency is promoted even if it does not restrict agriculture water use per se. This is due to the fact that in some locations where SGPI is undertaken land is available and accessible (e.g. desert areas). It has been showed that in these areas, any water efficiency improvements will not necessarily bring water savings as farmers can expand their irrigated area with the volume of water saved (Scott et al., 2014; Ward and Pulido-Velazquez, 2008).

5. Conclusions and policy implications

The development of SGPI is yet again another chapter in the current search for an environmentally sustainable balance within the WEF nexus, with important potential positive impacts on rural livelihoods. The implementation of this nexus approach requires however the integrated scientific re-assessment of resource-use efficiencies and environmental and financial sustainability in order to better inform national development strategies and more sustainable business models.

As presented above, SGPI has a role to play in solving agriculture's low efficiency problems and energy dependency but its benefits are yet to be fully appraised. State policies with financial subsidies lowering the cost of solar technology can mask the real costs of this technology for farmers. Moreover, the focus on cost and technology-efficiency comparisons (diesel pumps vs. solar-powered pumps) has distracted until now the discussion on the impact of state intervention in market regulation and financial incentives. A conundrum here arises as, on the one hand, subsidies can lead to market distortions but on the other they are required if this technology is to be made accessible to all. Additionally, without positive incentives such as reduced trade barriers, the financial and economic feasibility of this technology could be compromised. The recommendation here is that subsidies need to be targeted and tied to design regulations, water requirements, and accompanied with the monitoring of maximum pump and well extraction capacities.

At the same time, while governments are promoting this technology, implementation and policy gaps continue to exist. Despite the increasing reliability and affordability of off-grid SGPI, the recommendation is that state policies seeking to promote this technology for irrigation need to account for the direct and indirect impacts caused within the water-energy-food nexus and on groundwater resources in particular. When solar leads to over-abstraction, governments and international development agencies should reconsider their subsidies and support programs.

Institutional and regulatory arrangements can also be unclear when different ministerial competencies are involved. Poor or inexistent official quality standards and restricted financial products for farmers also add up to the list of potential barriers undermining the feasibility and development of this technology. Traditional line ministries require to be equipped with multi-sector integration strategies and solar energy subsidies and programs need to improve access to data, monitoring of pumping rates and capacities, and control well expansion and water use. The impact of SGPI for irrigation on poor and marginalized farming communities (including women) remains to be assessed. The conundrum land/technology/financial incentives also needs to be unpacked as equity issues regarding access to resources (groundwater and land) can easily arise, and could further limit the feasibility of these projects.

To summarize, the impacts of this technology are usually quantified at a macro-scale according to technical and economic parameters, failing to consider financial limitations and the localized impacts on natural resources. Access and availability of groundwater resources are not considered adequately in projects, which could lead to potential over-abstraction. The complex socio-economic and institutional contexts surrounding the development and use of this type of technology need to be further scrutinized, based on sound and contextualized research. As Radulovic (2005, 1883) wrote, the development and expansion of PV markets has to account for political constraints whilst assessing how this type of technology can improve development goals and cultivate “locally appropriate service delivery models.” Sustainability issues related to access, availability, and future abstraction of groundwater with effective monitoring are preponderant and have to be taken into account and examined before any solar irrigation project can be considered or conceptualized. Thus, a sustainable and integrated policy approach is therefore needed for the implantation of this type of technology, for decision-makers and practitioners aiming to address development gaps, water resource sustainability, and energy supply needs.

Uncited references

(King and Bulter (2010); Short and Thompson (2003); World Bank (2014)).

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References

Abu-Aligah, M., 2011. Design of photovoltaic water pumping system and compare it with diesel powered pump. Jordan J. Mech. Ind. Eng. 5 (3), 273–280.
Aguilar, D., 2011. Groundwater reform in India: an equity and sustainability dilemma. Tex. Int.l Law J. 46, 623–653.
Ahmad, S., Ali, I., 2011. Feasibility of sOlar Powered Pumping Systems for Deep Tubewells in Pakistan, Research Briefings, 3. Natural Resources Division, Pakistan Agricultural Research Council, Islamabad.
Barham, N., 2014. “The sociopolitical aspects of water scarcity in Jordan”, Conference on ‘Social water studies in the MENA region – State of the art and perspectives’, German Jordanian University Campus, 28-29 September 2014, Madaba, Jordan.
Bassi, N., 2015. Irrigation and energy nexus: solar pumps are not viable. Econ. Polit. Wkly. (1), 63–66.
Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., Gielen, D., Arent, D., Landfear, D., Zhengrong, S., 2013. Re-considering the economics of photovoltaic power. Renew. Energ. 329–338.
Bloomberg, 2016. New Energy Outlook 2016. Bloomberg New Energy Finance (BNEF). ⟨https://www.bloomberg.com/company/new-energy-outlook/#form⟩ (accessed 09.11.16).
Burney, J., Woltering, L., Burke, M., Naylor, R., Pasternak, D., 2010. Solar-powered drip irrigation enhances food security in the Sudano-Sahel. Proc. Natl. Acad. Sci. USA 107 (5), 1848–1853.
Chebaane, M., El-Naser, H., Fitch, J., Hijazi, A., Jabbarin, A., 2004. Participatory groundwater management in Jordan: development and analysis of options. Hydrogeol. J. 12, 14–32.
van Campen, B., Guidi, D., Best, G., 2000. Solar photovoltaics for sustainable agriculture and rural development, Environment and Natural Resources Working Paper No.2, Rome.
Chandel, S.S., Naik, M.N., Chandel, R., 2015. Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. Renew. Sustain. Energy Rev. 49, 1084–1099.
de Châtel, F., 2014. The role of drought and climate change in the Syrian Uprising: Untangling the triggers of the revolution. Middle East. Stud. 50 (4), 521–535.
Doukas, H., Patlitzianas, K.D., Kagiannas, A.G., Psarras, J., 2006. Renewable energy sources and rationale use of energy development in the countries of GCC: myth or reality?. Renew. Energy 31, 755–770.
FAO, 2014. The water-energy-food nexus. A new approach in support of food security and sustainable agriculture, Food and Agriculture Organization of the United Nations, Rome.
Fedrizzi, M.C., Ribeiro, F.S., Zilles, R., 2009. Lessons from field experiences with photovoltaic pumping systems in traditional communities. Energy Sustain. Dev. 13, 64–70.
Giordano, M., Villholth, K.G., 2007. The Agricultural Groundwater Revolution: Opportunities and Threats to Development. CABI, Wallingford.
GIZ, 2015. Solar energy farming in the Azraq Basin of Jordan, ACCWaM, GIZ.
Gopal, C., Mohanraj, M., Chandramohan, P., Chandrasekar, P., 2013. Renewable energy source water pumping systems – a literature review. Renew. Sustain. Energy Rev. 25, 351–370.
Hattingh, H., 2013. Report on Sekem study, ⟨https://drive.google.com/file/d/0BxbNeXH1Y54xc3FzcmhaTUtrTjA/view⟩ (accessed 17.05.15).
Howes, M., 1982. The potential for small-scale solar-powered irrigation in Pakistan. Commissioned study, Institute of Development Studies, University of Sussex.
Howes, M., 1984. The potential for groundwater exploitation by solar-powered pumps in Pakistan. Agric. Admin. 16, 229–248.
IEA, 2014. Technology Roadmap – Solar Photovoltaic Energy. International Energy Agency. ⟨https://www.iea.org/media/freepublications/technologyroadmaps/solar/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf⟩ (accessed 01.07.15).
IFC, 2014. Scaling up opportunities for solar-powered irrigation pumps. 2014 World Water Week, Stockholm, Sweden.
IRENA, 2016. Solar Pumping for Irrigation: Improving Livelihoods and Sustainability. The International Renewable Energy Agency, Abu Dhabi.
Kelley, L.C., Gilbertson, E., Sheikh, A., Eppinger, S.D., Dubowsky, S., 2010. On the feasibility of solar-powered irrigation. Renew. Sustain. Energy Rev. 14 (9), 2669–2682.
King, H., Bulter, A., 2010. “Malawi solar powered pump system”, 2010 ASEE Southeast Section Conference. 18-20, 2010) Virginia Polytechnic Institute and State University, Blacksburg, Virginia. (April 18-20, 2010) ⟨http://se.asee.org/proceedings/ASEE2011/Papers/FP2011kin150_163.PDF⟩.
Lazard, 2014. Lazard’s levelized cost of energy analysis – Version 8.0. ⟨https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf⟩ (accessed 08.11.16).
Lorentz, 2013. Solar water pumping for irrigation in Oujda, Morocco, Case Study 5, 01/2013, ⟨https://www.lorentz.de/pdf/lorentz_casestudy_irrigation_morocco_en-en.pdf⟩ (accessed 30.06.15).
Mahmoud, E., El Natherb, H., 2003. Renewable energy and sustainable developments in Egypt: photovoltaic water pumping in remote areas. Appl. Energy 74 (1–2), 141–147.
Meah, K., Ula, S., Barrett, S., 2009. Solar photovoltaic water pumping – opportunities and challenges. Renew. Sustain. Energy Rev. 12, 1162–1175.
Nederstigt, J., Bom, G.J., 2014. Renewable energy for smallholder irrigation. A desk study on the current state and future potential of using renewable energy sources for irrigation by smallholder farmers, SNV.
Paulsen, J., Reynolds, T., 2010. Alternative energy pumps to irrigate smallholder farmers’ land: what is the state of the art?, EPAR Brief No.102, Evans School of Public Affairs, University of Washington.
Purohit, P., 2007. Financial evaluation of renewable energy technologies for irrigation water pumping in India. Energy Policy 35, 3134–3144.
Purohit, P., Kandpal, T.C., 2005. Solar photovoltaic water pumping in India: a financial evaluation. Int. J. Ambient Energy 26 (3), 135–146.
Radulovic, V., 2005. Are new institutional economics enough? Promoting photovoltaics in India's agricultural sector. Energy Policy 33 (14), 1883–1899.
REN21, 2013 REN21, 2013. MENA Renewables Status Report, UAE Ministry of Foreign Affairs' Directorate of Energy and Climate Change, IRENA – International Renew. Energ. Agency, REN21 – Renew. Energ. Policy Network for the 21st Century.
Rosenblum, L., Bifano, W.J., Scudder, L.R., Poley, W.A., Cusick, J.P., 1978. Photovoltaic water pumping applications: assessment of the near-term market, Report No. NASA TM-78847, Lewis Research Center, Cleveland, National Aeronautics and Space Administration.
Sahin, A.Z., Rehman, S., 2012. Economical feasibility of utilizing photovoltaics for water pumping in Saudi Arabia. Int. J. Photoenergy 2012, 1–9.
Scott, C.A., Vicuna, S., Blanco-Gutierrez, I., Meza, F., Varela-Ortega, C., 2014. Irrigation efficiency and water-policy implications for river basin resilience. Hydrolo. Earth Syst. Sci. 18, 1339–1348.
Shah, T., Kishore, A., 2012. Solar-powered pump irrigation and India’s groundwater economy: a preliminary discussion of opportunities and threats, Water Policy Research Highlight, 26, IWMI-Tata Water Policy Program.
Shah, T., Verma, S., Durga, N., 2014. Karnataka's smart, new solar pump policy for irrigation. Econ. Polit. Wkly. XLIX (48), 10–14.
Short, T.D., Thompson, P., 2003. Breaking the mould: solar water pumping – the challenges and the reality. Sol. Energy 75 (1), 1–9.
Smith, D.V., Allison, S.V., 1978. Micro irrigation with photovoltaics, MIT Energy Laboratory Report –MIT –EL-78-006.
Van Pelt, R., 2007. Solar-powered groundwater pumping systems for domestic use in developing countries. University of Minnesota. ⟨https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCEQFjAA&url=https%3A%2F%2Fwiki.umn.edu%2Fpub%2FEWB%2FUganda_Groundwater_Supply%2FSolar_Pumping_of_Groundwater.doc&ei=asOSVa79HeLXyQObhbCwCw&usg=AFQjCNFA7q6×7wFybLB9xk-lSpJ27E6u0g&sig2=upVpBlEOzsLQewDdcRvGyA&bvm=bv.96783405,d.bGQ⟩ (accessed 30.06.15).
Ward, F.A., Pulido-Vazques, M., 2008. Water conservation in irrigation can increase water use. Proc. Natl. Acad. Sci. USA 105 (47), 18215–18220.
Ward, P.R.B., Dunford, W.G., July 1984. Solar powered groundwater pumping for medium heads. In: Proceedings of the Harare Symposium Challenges in African Hydrology and Water Resources, Harare, pp. 249–300.
World Bank, 1981. Small-scale solar-powered irrigation pumping systems, Phase I – Project Report, UNDP Project GLO/78/004 Executed by the World Bank.
World Bank, 2014. Project paper on a proposed additional credit in the amount of SDR 50.58 million (USD78.4 million equivalent) to the People's Republic of Bangladesh for a rural electrification and renewable energy development II (RERED II) project May 23, 2014,. The World Bank, Washington DC.
World Bank, 2015. Solar PV Water Pumping in Yemen – draft for comment, ⟨http://www.moit.gov.ye/moit/sites/default/files/Solar%20PV%20Water%20Pumping%20%20Study%20in%20Yemen%20World%20Bank.pdf⟩ (accessed 30.06.15).
Yu, Y., Liu, J., Wang, H., Liu, M., 2011. Assess the potential of solar irrigation systems for sustaining pasture lands in arid regions – a case study in Northwestern China. Appl. Energy 88, 3176–3182.

Zeitoun, M., Allan, T., al Aulaqi, N., Jabarin, A., Laamrani, H., 2012. Water demand management in Yemen and Jordan: addressing power and interests. Geogr. J. 178 (1), 54–66.