A review of sustainable solar irrigation systems for Sub-Saharan Africa

Saeed Mohammed Wazed[a,*], Ben Richard Hughes[a], Dominic O'Connor[a], John Kaiser Calautit[b]

[a] Energy2050, Mechanical Engineering, Faculty of Engineering, University of Sheffield, Sheffield, South Yorkshire S10 2TN, United Kingdom
[b] Department of Architecture and Built Environment, University of Nottingham, Nottingham NG7 2RD, United Kingdom

ARTICLE INFO

ABSTRACT

This investigation focused on the research undertaken on solar photovoltaic (PV) and solar thermal technologies for pumping water generally for irrigation of remote rural farms specifically considering the Sub-Saharan African region. Solar PV systems have been researched extensively for irrigation purposes due to the rise in Oil prices and the upscaling in commercialisation of PV technology. Based on the literature the most effective PV system is presented for the irrigation of a small scare remote rural farm with respect to the cost, pumping capacity and system efficiency. Similarly, solar thermal systems are reviewed and the most effective system described. Unlike PV technology, solar thermal technology for water pumping is lacking especially in small scale operations. However, with the possibility of local production, low investment cost, easy maintenance and lower carbon footprint, solar thermal water pumping technologies may be able to overcome the shortcomings of the PV technology that has stopped widespread use of the technology for irrigation applications. Taking into consideration recent developments in concentrated solar technologies using the Stirling engine, novel solar thermal water pumping systems may be developed. This review also highlighted the different methodologies such as modelling, used to investigate and optimise the performance of solar powered systems.

1. Introduction

Population growth and food insecurity necessitates an increase in farming and irrigation all over the world. The focus here is not only to produce more but to do so in a manner that protects the environment. Moreover, the impact on poorer nations, which are already struggling with food shortage, is far more adverse than others as more land and energy is required to meet the requirements of the future. This creates a need for the development of sustainable technologies that can be implemented to utilise the readily available local resources to drive the cost of the irrigation systems down.

The Sub-Saharan region in Africa is one such region that is marred by inconsistent supply of safe water supplies. Contaminated ground water and long dry spells means that the main source of water in these regions are the rich groundwater reserves. Only 10% of this region utilises groundwater and most of this stems from the lack of economic incentives [1]. The cost of harvesting the reserves are very high. Not only is the initial investment high for purchasing generators and pumps but also the ongoing inflation in fuel costs leads to a consistent increase in operational and maintenance costs [2]. Such costs are extremely high for remote small scale independent farmers to bear.

The focus of this review is to investigate affordable irrigation systems that will be portable and utilise the local resources for manufacture and maintenance. Emphasis is also provided on the use of renewable energy resources to negate the requirement of fossil fuel driven motors (generally diesel powered) and pumps to further reduce the running cost of irrigation. Severe draught, lack of rain and long dry spells provides the opportunity for the utilisation of solar power in Sub-Saharan Africa, with both solar thermal and Photovoltaic (PV) technologies [3], and hence, is considered the focus of this review.

In the review, solar thermal and PV technologies will be compared on the basis of cost, power output and flow generated. The above parameters have been selected in order to design a system that will be viable for the independent farmer for irrigation of remote small scale farms in the Sub-Sharan African region with average small scale farm size of 1 ha according to the Food and Agriculture Organisation (FAO) [4].

The research on solar thermal power has not been as prominent as PV panels in recent times for water pumping applications. However, major development in solar thermal technologies incorporating Stirling Engines warrants a review of solar thermal systems for irrigation because of it's potential to work at low temperatures and relatively simple construction. This review paper highlights major technological developments made in PV irrigation systems, solar thermal irrigation systems and new developments in solar thermal technology that could be utilised in irrigation, with focus on medium to low powered Stirling

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* Corresponding author.
  E-mail address: SMohammedWazed1@sheffield.ac.uk (S. Mohammed Wazed).

cycle engines. The findings are summarised and the performance of the systems are compared to identify the key advantages and disadvantages of each technology.

2. Research methodology

A literature review is performed on PV and solar thermal irrigation systems. While there is numerous research on PV and Solar thermal technologies, the focus on this review is to study the implementation of the technology in irrigation. To obtain the research material for this literature review, keyword search has been utilised incorporating, "solar water pumps", "solar irrigation", "PV irrigation", "solar thermal irrigation", "PV water pumping systems", "Stirling pumps", "Rankine Cycle water pumps", "ORC water pumps", "ORC irrigation" and "Stirling Irrigation". No location bias has been set. The University of Sheffield's "StarPlus Library Discovery" search tool, "Science-Direct" search engine and the "Google" search engine has been utilised.

PV system reviews have been divided in 4 sections:

- PV irrigation technology reviews – Contains reviews of papers which enlists the various PV technologies that have been studied in the years prior to the publication.
- PV irrigations systems – Contains reviews of papers which describe unique irrigation systems design.
- PV irrigation systems performance – Contains reviews of papers that discuss technologies and control systems that can be used to optimise PV irrigation systems
- PV irrigation technology in comparison to other technologies – Contains reviews of papers that compare PV irrigation technologies against other technologies including Diesel generated pump systems and Renewable energy generated pump systems.
    Solar Thermal system reviews have been divided in 3 sections:
- Solar thermal irrigation technology reviews – Contains reviews of papers which enlists the various solar thermal technologies that have been studied in the years prior to the publication.

- Conventional solar thermal technologies – Contains reviews of papers discussing solar thermal technologies based on the Rankine cycle.
- Unconventional solar thermal technologies – Contains reviews of papers discussing solar thermal technologies based on Stirling cycle and other two stroke systems.

After the literature review was performed each solar powered technology (PV and Solar Thermal) is then individually analysed. A summary table of all the technology systems reviewed is presented and the best irrigation set-up has been established. Following this the future of solar irrigation technology is discussed.

3. PV irrigation systems

PV Technologies convert solar energy into electrical energy and then coupled with an electric motor is used to drive an electric pump. Fig. 1 depicts a typical PV irrigation set up. This system can be further enhanced depending on the output requirement, charge regulation based on the requirement of the pump (AC/DC) as well as the incorporation of a battery to counter the fluctuation of solar irradiation available throughout the day or even for irrigation at night, when lower water losses and higher irrigation uniformity is observed [5].

The water outlet from the irrigation system (depicted in Fig. 1) can be used either directly for irrigation or can be used to fill up a water storage tank. An advantage of the water storage tank is that it can be a substitute of the battery system, wherein the potential energy of the stored water can be utilised for drip irrigation.

Photovoltaic systems are generally very simple to implement, and an adequately designed system is efficient and can compete with other
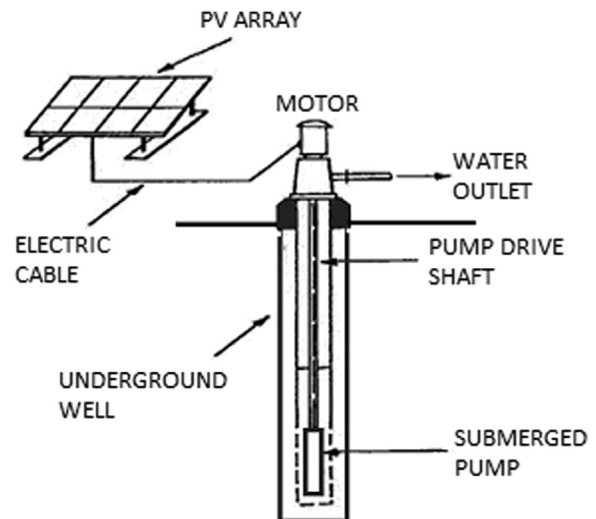

Fig. 1. Schematic of a simple PV irrigation set up for groundwater retrieval [6].

systems when operational and maintenance costs are considered. However, the initial investment is often identified as a major turn off [7]. While PV systems are easier to maintain than most other renewable energy systems, there are lots of factors that limit its use including, inconsistent solar irradiation, expensive tracking systems, reduction in efficiency due to overheating of panel systems, lower output due to energy conversion and one of the major issues identified in recent times is the large environmental impact in the production of PV panels [7–9].

A decrease in the cost of PV technology has meant many rural developments have been keen on utilising the technology because of this, a great amount of research has been conducted on solar PV technologies for water pumping in the recent years so much so that photovoltaic irrigation systems have become synonymous with solar-powered irrigation. Significant research has been conducted on performance, feasibility and economic viability of various PV systems as detailed below.

3.1. PV irrigation technology reviews

Chandel et al. [10] reviewed technologies for irrigation and supply of drinking water to communities that utilises solar PV technology. The study focussed on new technology updates, efficiency, analysis of the performance, efficient sizing of panels, degradation of supplying power to the pump from the PV panels and the economic and environmental aspects of utilising PV technology. In comparison to diesel / conventional electric system, PV systems were identified to be more economically viable in urban and remote rural areas with a payback time of 4–6 years achieved. For shallow wells (10–20 m deep), AC motor pump systems showed similar water output levels when compared to DC motor pump systems, however, at higher depths (30–50 m) DC motor systems provide higher flowrates. The efficiency of different types of solar cells are as per indicated in Table 1 (as tabularised by Green et al. [11]) with Multijunction five-junction cells demonstrating the highest efficiency of almost 39%. Thin film CdTe cells, which are widely available commercially, are rated at an efficiency of 21%.

The efficiency of the system can be further improved using positive displacement pumps, diaphragm pumps and progressing cavity pumps were capable of pumping efficiencies of up to 70%. A Maximum Power Point Tracking [12] system could be utilised for further increasing the efficiency of the PV water pumping system by converting the high voltage from the DC output of the PV panels to a lower voltage for charging of batteries. The power degradation in PV modules was established to be 0.8% per year as a result of prolonged field exposure and requires further research [13]. While automatic tracking helped in increasing the efficiency, the cost was too high; instead double axis

Table 1
PV cell efficiency at 25 °C and 1000 W/m^2 [11].

PV cell materials type	Efficiency (%)	PV cell materials type	Efficiency (%)
Silicon		Dye mini module	10.7 ± 0.4
Si (crystalline)	26.3 ± 0.5	**Thin-film chalcogenide**	
Si (multi-crystalline)	21.3 ± 0.6	CIGS (cell)	21.0 ± 0.6
Si (thin-film minimodule)	10.5 ± 0.3	CIGS (minimodule)	18.7 ± 0.6
III–V cells		CdTe(cell)	21.0 ± 0.4
GaAs (thin film)	28.8 ± 0.9	**Multi-junction devices**	
GaAs (multi crystalline)	18.4 ± 0.5	Five-Junction Cell (bonded)	38.8 ± 1.2
InP (crystalline)	22.1 ± 0.7	InGaP/GaAs/InGaAs	37.9 ± 1.2
Dye sensitised		a-Si/nc-Si/nc-Si (thin film)	14.0 ± 0.4
Dye	11.9 ± 0.4	**Si (amorphous)**	10.2 ± 0.3

manual tracking systems were suggested to be implemented which helped improve the system efficiency by 20% and were relatively cheaper. The main factors affecting PV panels were dust accumulation, over heating of PV modules and fluctuation of solar irradiation. To counter the inconsistence in solar irradiation carefully modelled battery systems were suggested to be implemented to ensure economic viability, spraying with water assisted in both dust clearance and cooling of the modules.

Sontake and Kalamkar [9] conducted a comprehensive review of PV water pumping systems encompassing literature from various fields of engineering between the years 1975–2014. The review breaks down the different types of technologies based on site specific designs, site specific performance, performance of the solar pump using different motors, different ratings of PV panels and investigating implement MPPT models. Cost reduction methods were also investigated, and it was found that 60% of the cost could be reduced by manufacturing PV panels locally. The study also discussed new concepts and design ideas that could be utilised to enhance the effectiveness of the PV panels, reducing the complexity as well as reducing the costs focusing on low capacity PV pumps.

In the review, regions in Africa showed great promise, especially northern and Sub-Saharan African regions, in both Sudan and Egypt PV water pumps was seen to be able to efficiently pump water and provided low operating costs. In Nigeria, the pump performance was seen to be satisfactory providing 20 m^3/day [14]. Research in Algeria also provided positive results concluding that PV water pumps could sufficiently pump water for small scale farm sized under 2 ha [15]. That said, site specific research was proposed, as the performance of pumps was seen to be 10–25% less than that claimed by the manufacturer [16]. The Various parameters that influence PV pumping technology has been summarised as per Fig. 2.

The research estimates a range of optimal power output that can be produced at a solar radiation of 1000 W/m^2, wherein, 1 m^2 panel area could produce 100 W, and 17 m^2 area could produce 900 W output. It was also proposed that diaphragm pumps with DC motor be used for small capacity pumps while centrifugal pumps with induction motor would be preferable for higher capacity pumps [9]. Helical pumps were also shown to be suitable for high heads of over 50–150 m with Grundfos 6SQF-2 pump showing no loss after 3 years' performance [18]. DC motors has been the preference for 80% of the research conducted showing the highest efficiencies with 10% research showing AC motors providing higher efficiencies for higher capacity pumps, however, the increase in efficiency is minimal. Development in DC motors such as Permanent Magnet Synchronous Motors which are brushless motors and use permanent magnets instead of winding rotors compared to conventional DC motors, further elevates the potential of DC motors.

Research has shown that because of the losses incurred on PV systems, 16% of the work potential of the PV panels are lost [19]. Few ways to reduce this loss has been proposed including the implementation of tracking, cleaning of panels and cooling of the panels as at higher temperatures the panels show lower efficiencies. Furthermore, computer assisted design has been proposed to optimise the various components of the PV water pump system. Optimisation by implementing MPPT for pumps is shown to increase efficiency by 35% [20] and water pumped quantity was increased by 7.4% [21].

Though overheating is an issue boosting with reflectors during days of lower radiation can enhance the power output of the PV system as observed in Fig. 3.

3.2. PV irrigation systems

Deveci et al. [22] designed and developed a drip irrigation system that utilises solar PV power for a project in Turkey covering 1000 m^2 and containing over 100 trees, it was considered that it would require 1450 l of water/day. From June to October, the site was irrigated 2 h a day with the help of an automatic timer. The PV panels (generating 132 Wh/day using two 10 W PV panels to generate 12 VDC) charged a battery (14 Ah, 12 VDC) buffer throughout the day during available sunlight using Maximum Power Point Tracker (MMPT) to increase the PV conversion efficiency to operate at the maximum power point of the I-V curve. The DC pump was powered by the batteries providing consistent voltage and hence optimal performance of the pump. While other research considers using of the battery to drive the cost, Deveci et al. argued that utilising the battery ensures that the overall cost of the system decreases by 63%, thus ensuring better payback and hence making the system cheaper overall. This could allow the use of cheaper PV technology. To better understand of the system characteristics, a context diagram is presented in Fig. 4.

Setiawan et al. [23] designed a PV powered water pumping system to supply water in a village in Indonesia. The systems consisted of 32 panels that produced 3200 Wp and operated 2 submersible pumps (Lorentz PS1800 HR-05HL) to provide a flowrate between 0.4–0.9 l/s and a total head of 218.34 m. The system consisted of 4 stacks of 8 solar cells connected in series, with 2 stack connected in parallel feeding each pump. The pumps are in turn connected in parallel to provide the ultimate head. The Project was funded by Ministry of Research and Technology Republic of Indonesia in conjunction with the Ministry of Public Works however, the costs associated with the system are not indicated. The system designed was optimal in providing clean water to the village where previously the inhabitants would use stored rainwater for survival.

Campana et al. [24] devised a novel optimisation process by which PV water pumping systems could be economically optimised for irrigational purposes. A simulation considering the availability of groundwater, water supply, the investment costs, and the revenue from the crop sale has been developed. To prove the effectiveness of this approach, the simulation is applied to an existing PV water pumping system with the results showed positive impact guaranteeing continuous operation, reducing PV array size and thus reducing the investment and thus lowering the payback period. Nine PV modules, positioned at a tilt angle of 42° and −32° surface Azimuth angle, were proposed to produce 1.44 kWp powering a 1.1 kW Centrifugal AC pump. However, as per the simulation, due to the low rate of replenishment of the ground water resource, the specifications of the system had to be downgraded to produce 0.96 kWp, which in turn decreased 18.8% of the investment capital. The study enforced the use of natural groundwater level replenishment so that the cost of foraging for water source can be reduced as well as protect the groundwater source from being over used. Fig. 5 demonstrates the relation between annual profits and pump capacity at US\$ 1/Wp and US\$ 2/Wp and establishes that with adherence to the ground water level constraints,
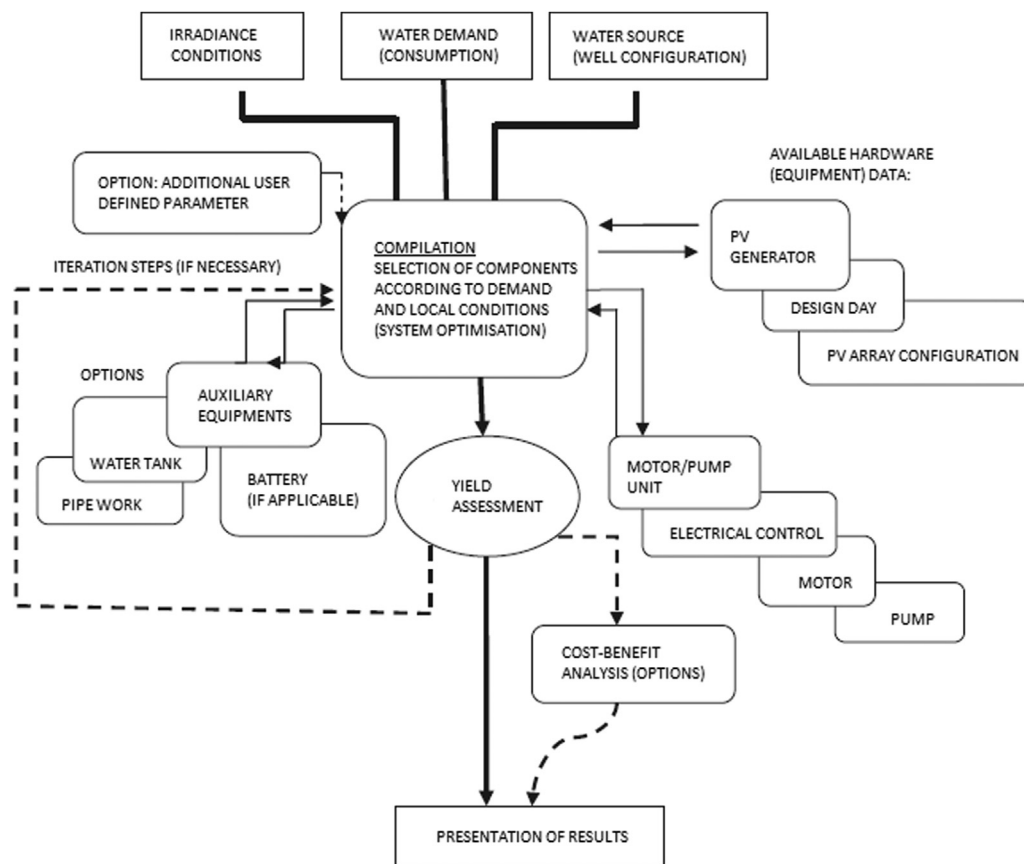
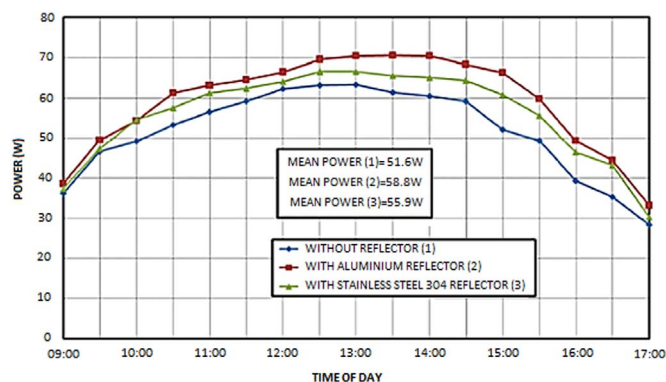Fig. 2. Parameters that influence PV water pump design [17].

Fig. 3. Power output comparison with and without solar irradiation boost [9].

the most feasible solution is a PV water pump just shy of 1 kWp at US$ 1/Wp.

López-Luque et al. [25] proposed a standalone design for a direct pumping PV system for the irrigation of olive orchards optimised with the help of a simulation model for "deficit irrigation" leading to reduction of cost and water savings. The model simulates, the power of the PV system, the balance between energy and water of the irrigation system and the yield of the crop. Using this, the cost of operation of the system and the profit margin was evaluated. The system allowed for a certain level of water stress on the crops if the yield of the crop was not affected. The demand was reduced and thus the system implemented could be cheaper while at the same time saving water. On evaluating a case study in Spain, the optimal power requirement was evaluated as 150 W/ha for 40 m head, 250 W/ha for 60 m head and 300 W/ha for 80 m head for "deficit irrigation" wherein, the plants are irrigated lower than the prescribed amount which

requires a thorough understanding of the plant's yield response. For full irrigation, the results were 300 W/ha for 40 m head, 400 W/ha for 60 m head and 600 W/ha for 80 m head. The system was found to be feasible for "deficit irrigation" but not full irrigation. "Deficit irrigation" tactics also provided 4–6% of water saving.

Hossain et al. [26] studied the suitability of utilising solar powered irrigation in Bangladesh for the cultivation of Rice, brinjal (eggplant), tomato and wheat both in the technical and economic sense. Pumps were stationed in 4 different places and the performance of the pumps were tested measuring the solar radiation, voltage and current generated, flowrate and the head. The drip and furrow methods were implemented in the research. Eggplant and tomatoes were tested using both drip and furrow method while wheat was tested using just the furrow method, the method used for rice cultivation was not specified in the study. Around 0.5 ha land was considered for all crops except for rice which was cultivated in a 0.2 ha land. The pump was powered by Solar panel providing between 1050 and 1440 Wp. Considering all four locations, the lifetime profit to cost ratio of utilising the PV powered irrigation system was determined for each crop with tomato, brinjal and wheat shown to be between 2.22–2.34, however, rice was merely 0.31. This is as per pump cost of US$ 5700, a life of 20 years and an average discharge of 100 l/minute. 50% of water was saved using drip irrigation of tomatoes and brinjal. Rice cultivation, however, was not seen as economically viable using PV powered irrigation system method due to the low yield, high water requirement (3 times that of the other products).

Kumar et al. [27] conducted field experiments and testing of a gravity-fed type drip irrigation system powered by solar PV for a small land of 18 m × 6 m area. The study was conducted in Central India. Water from a pond was pumped to a storage tank (1000 L) and applied for irrigation as per the Star Configuration irrigation system which contains four micro tube emitters joined at a central connector
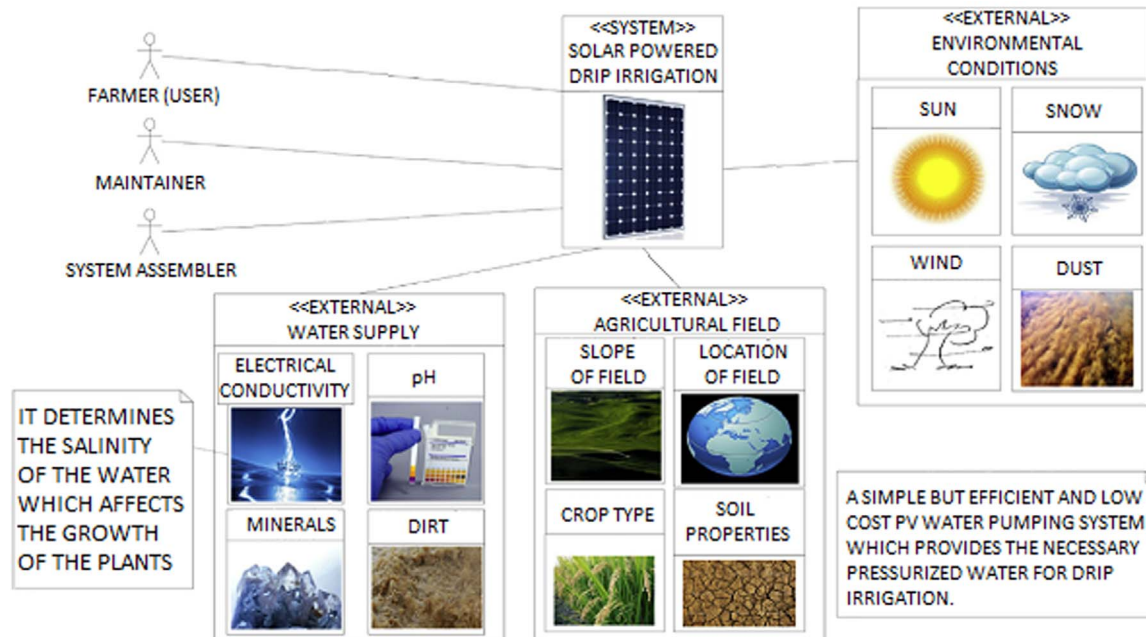
Fig. 4. Context diagram representing drip irrigation system powered by PV [22].
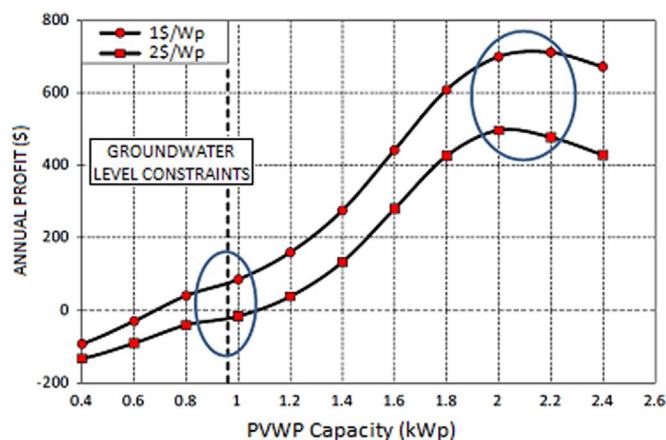

Fig. 5. Pump capacity vs annual profits with constrained groundwater levels [24].

accessing water from the sub main through another connecting microtube [28]. The pumping system consisted of 148 W solar panel and a minimum power voltage of 15 V, power current 4-% A, fitted with a 12 V battery with a capacity of 10 A for 5 h, an AC type inverter powering an AC pump of 60 W drive, input power of 110 W and discharging at 15 l/min. The overall cost of the set-up was US $410 including the cost of solar panels, solar charge control unit, battery with accessories, inverter, pump, overhead tank and civil works. See Fig. 6 for the schematic diagram of the set-up. It was established that this system would be enough to irrigate 0.2 ha of land. As a very small test area was considered, the overall head loss during the conveyance of the water from the storage tank to the crops was almost negligible. The system was recommended to be run between the times of 11 a.m. and 3 p.m. when maximum irradiation could be used and that would be enough for the irrigation needs for a day.

Reca et al. [29] conducted a feasibility analysis of the profitability of a direct pumping PV system that would work standalone and be used for irrigation in Spanish greenhouses (18 °C and 3000–3600 sun hours per year, 0.75 ha/greenhouse, drip irrigation, required 3 l/hour, 40 m pump head, 8720 W/ha), see Fig. 7. A simulated model comprised of PV power generation, pumping management, and irrigational water requirements was prepared. Several sectors were considered and two strategies of management of irrigational services were established either to irrigate each sector one by one or to group irrigate sectors.
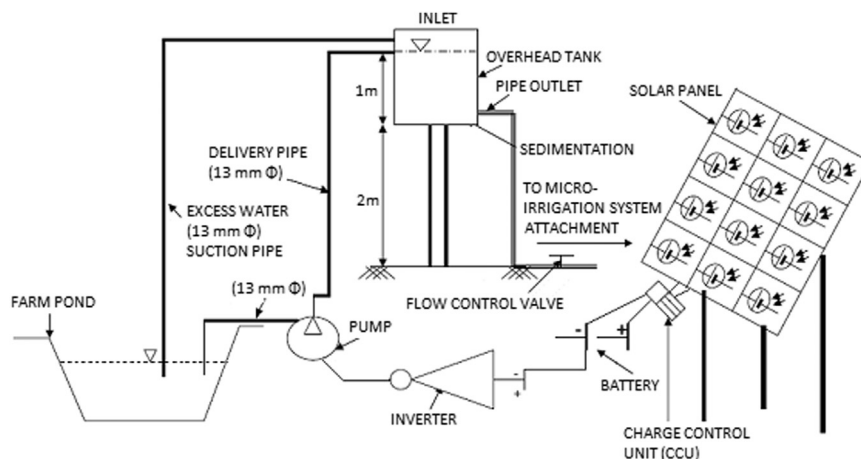

Fig. 6. Schematic diagram of micro-irrigation system powered by solar PV [27].
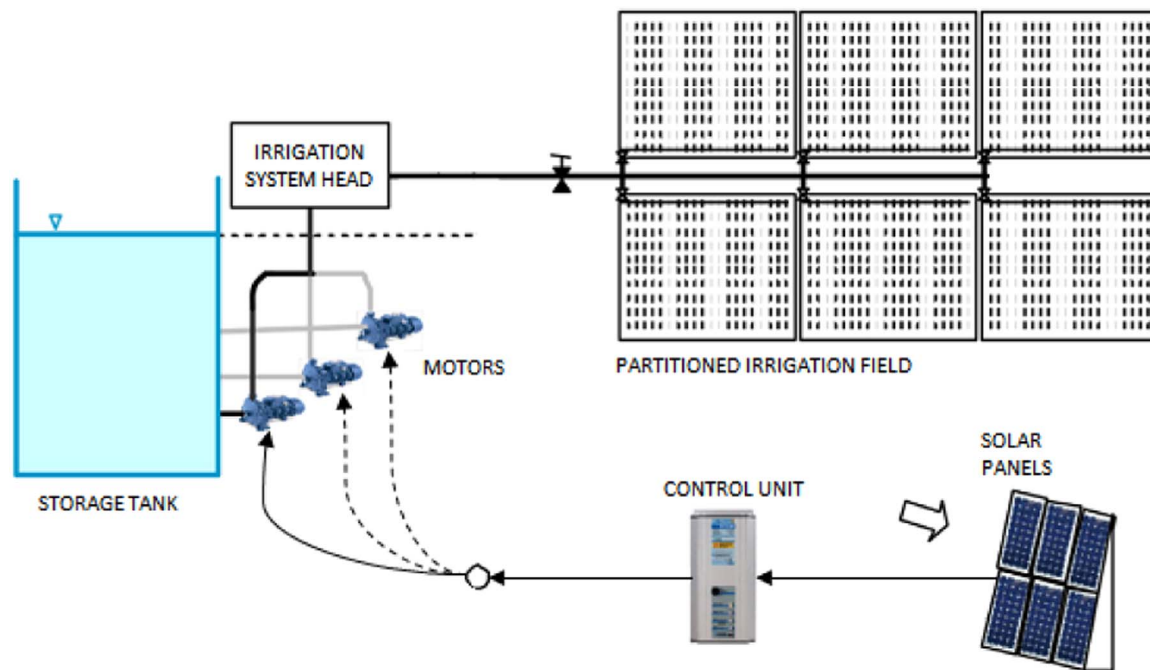
Fig. 7. PV irrigation system management layout [29].

The simulation proposed that irrigation of one sector at a time was more profitable than group irrigation, as that would require bigger and more expensive pumps. Profit was obtained by assigning 4 sectors in a hectare, however, the profit margin and efficiency of the system was still low with the highest Net Positive Value (NPV) obtained with 6 sectors, after which the NPV decreased. The profitability of the system could be improved if, the excess produced electricity from the PV panels could be used for other purposes.

3.3. PV irrigation systems performance

Chandel et al. [30] published the analysis of degradation of a mono-C-Si PV module (33 W rated, 1 m × 0.38 m) that had been exposed in the field for 28 years In the western Himalayan region of India. The PV module was used for a direct coupled PV water pump and the study's main objective was to identify the impact on the water pump caused due to the PV degradation. Visually the defects identified by the study were discolouration, oxidation of anti-reflective coating and the grid fingers and bubble formation causing delamination in the back sheet. Using a 1 m × 0.38 m sized PV panel producing 373 W, a head of 10 m was obtained with a discharge of 5500 l/h. The degradation for this system was measured to be 1.4% per year using visual, thermal imaging and indoor I-V characteristic measurements of modules under a sun simulator. The results coincided with studies undertaken previously, however, the results showed increase in open current voltage which was expected to reduce, this aspect requires further investigative study.

Yahyaoui et al. [31] modelled the management of an autonomous watering system using "Fuzzy Logic" [32] for energy and water for drip irrigation in a semi-arid district for production of tomatoes supported by PV panels and batteries. The water volume needed by tomatoes was first evaluated during the production cycle across March - July, then the PV panels, batteries and water pumps would be controlled based on the energy availability. The algorithm considered the semi-arid conditions depicted in Tunisia for the irrigation of 10 ha land at 200 m³/h before sunrise. Based on the study only 20% of the required power came from the battery, while 80% from the PV panels with a control system regulated the usage of power and helped elevate the battery life and increased the overall efficiency of the system.

Rawat et al. [33] reviewed the different ways of modelling and

optimisation of size and design methodologies of standalone and grid connected PV water pumping systems in India. A PV system including an array of PV cells, converter, inverter and a battery storage system is considered. To ensure that the PV system performs optimally, equations have been developed for modelling and design methodologies. The study concludes that PV systems are better sized when long term data of the site is available, numerical methods for sizing the PV systems are as good as the data available. In the case of inferior data, more intelligent systems need to be implemented to for better optimisation, such as "fuzzy logic", however these techniques are more complex and would require more expenses. The other factors to efficiently size PV systems are the efficiency curve of inverters, Load management and the motor torque.

Jones et al. [34] analysed the economics behind the use of PV water pumping at variable speeds in conjunction with a desalination system without the use of energy storage for agriculture. See Fig. 8 for various configurations suggestions of a desalinated water irrigation pump system. For comparison, the PV system was put up against diesel systems and systems utilising energy from the grid. The study was conducted in Jordan and focuses on 15−120 kW size for desalination of water salinity range of 1500−7500 ppm and at depths of 25−100 m. The study found that using large system sizes greatly reduces the price of desalination with a 15 kW system costing US$ 1.55 /m³ while a 111 kW system costing at US$ 0.7 /m³. PV technology was seen to be less economical than grid-powered systems but more economical than diesel powered systems. Furthermore, PV systems was shown to be more profitable for crops that provide high returns and low water consumption, shallow groundwater levels and low salinity levels.

Muhsen et al. [7] examined water pumping systems utilising photovoltaic technology featuring the modelling, design procedures, control strategies, field performance, reliability and feasibility of PV systems. Based on the review conducted, the highest system efficiency of 7% was observed for a system using helical pumps providing 0−8.4 l/min of flowrate in the Amarillo Texas region [35]. The highest average flowrate of 2600 l per hour was quoted to be generated for a 990 Wp system in Algeria with 11 m head giving a productivity of 9498.030 m³/kWp per year, the efficiency of the system was 1.299% without shading and 0.83% with shading [36]. The most extensive research was conducted on a 3−5% efficient system with a size of 2kWp
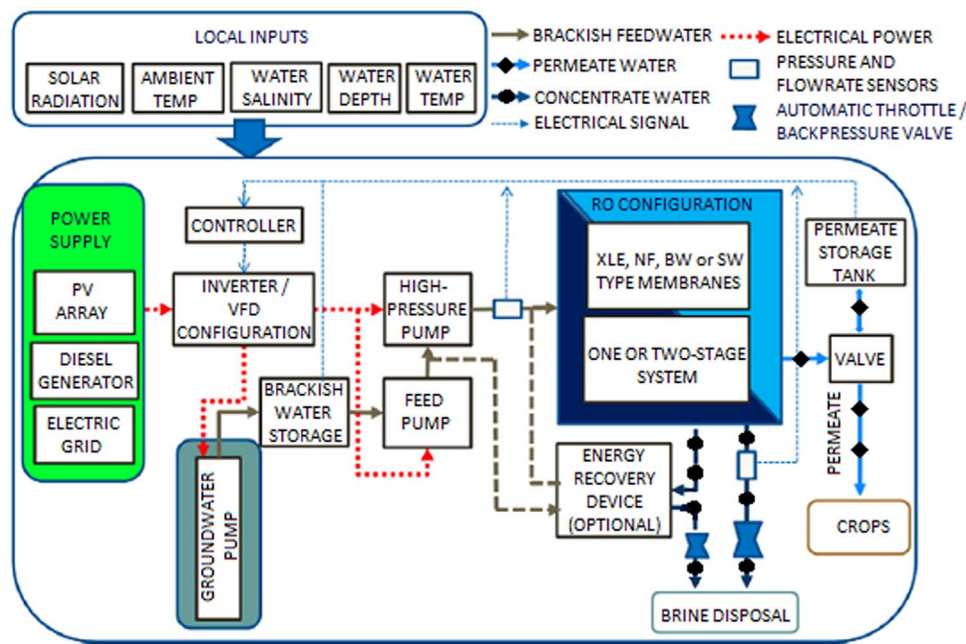
Fig. 8. Various configurations for set up of desalinated water pumping system [34].

capable of water head of 5–125 m and was conducted in seven different countries however, this research was done 20 years ago [37]. On average, the overall efficiency of systems is about 3.4% with an average annual water pumped being 6580.611 m³/kWp. The study highlighted that the most effective way to size the PV modules is using numerical sizing and control works utilising traditional MPPT.

Campana et al. [38] Investigated the most suitable locations in China where PV water pumping systems could be implemented for irrigation of grasslands. The assessment was made using an optimisation model of renewable energy systems that was spatially explicit based on overall minimisation of cost of the supply chain. The study demonstrated that PV water pumping systems provide a high potential for the improvement of forage productivity to meet the local demand. Land area of 1 ha was considered for a micro irrigation system and a hydraulic head of 20 m was established powered by a 1.44 kWp PV panels [39]. It was established that an increase of 25% in the yield of forage from grasslands resulted in 300% increase in the production of forage using PV water pump irrigation systems.

Elkholy and Fathy [40] developed an Artificial Neural Network (ANN) trained by a Teaching Learning Based Optimisation Algorithm (TBOA) [41] to obtain maximum power from solar panels by regulating the inverter voltage and frequency. The TBOA is an algorithm designed on the basis of the teacher-student relationship of learning to solve continuous and nonlinear functions to find a global optimal solution. The authors modelled an irrigation system that consisted of a PV array (116 × 71.3271 W connected in series) with a three-phase induction motor that drives a centrifugal pump (220/380 V, 1.1 kW, 50 Hz) for pumping water on MATLAB and Simulink. Based on the simulations undertaken, the efficiency of the system incorporating the ANN-TLBO method was higher than the voltage-frequency control method between 100 and 500 W power generation, however, over 600 W generation, the efficiencies of methods were closer.

Closas and Rap [42] investigated the impacts, opportunities and limitations of PV powered water pumping systems that utilise ground water reserves. The authors show that most projects overlook the true financial and economic costs of the technology and the use of the water resources which adversely affects the environment negatively. The study insists that link between water, energy and food must be balanced and this can only be possible when accurate data is provided. Monitoring of Ground water is deemed paramount so that the sustainability goals of the

technology is met and the livelihood of the future inhabitants are not threatened. The data obtained would be used not only to design the adequate irrigation system, but also can assist in regulation of subsidies and thus avoid "market distortions". The paper has adequately described key aspects often overlooked when new irrigation technology is being developed this is true for every irrigation system, however, the authors have focused only on PV powered systems.

3.4. PV irrigation technology in comparison to other technologies

Campana et al. [43] discussed the technological and economic feasibility of renewable energy systems for irrigation and conservation of farmlands in China, comparing PV water pumping technology to wind powered water pumping systems. Based on the irrigation water requirement (calculated as per FAO [44]), a model was developed to calculate the size of PV and wind powered systems based on varying solar irradiation and wind speeds respectively. A storage system or battery was considered as they are shown to impact adversely to the cost. The alfalfa plant was considered for the simulation model which has a plant density of 75,000 plants per hectare, 90% canopy cover, growing between May to September (140 days). The PV system produced a capacity of 2.9 kWp (at 2 $/Wp) while wind power generated 2.6 kWp (at 5.5 $/Wp) to power a 2.2 kW pump with the PV water pump irrigated land having higher produce than that irrigated with wind power. The study established that depending on the site wind powered systems can compete with PV systems, however, PV systems overall have more potential and better performance.

Treephak et al. [45] conducted an economic evaluation to compare PV powered and gasoline powered water pumping systems for irrigation and cultivation of rice. A 1.6 acre of land irrigated for 25 years was considered for the analysis and the fuel cost required for the pumping of water for the cultivation of rice is considered. With the same conditions, PV powered systems consisting of PV panels along with four different configurations are analysed including, AC motor without battery (S1), DC motor without battery (S2), AC motor with battery (S3) and DC motor with battery (S4). See Table 2.

Treephak et at. shows that stirring away from a gasoline powered system, the solar panels would save US $280 every year of fuel cost. From the analysis, a DC motor system without battery provides the highest economic value.

Table 2
Economic analysis of different PV systems [45].

Scenario	Motor size (W)		Battery	Inverter (W)	Solar panel	Estimated cost	Payback period (years)
	AC	DC					
S1	750	–	–	1500	250 W (× 6)	$2800	10.1
S2	–	500	–	–	250 W (× 4)	$2000	7
S3	375	–	85 Ah (× 4)	1200	295 W (× 4)	$2800	13.5
S4	–	250	60 Ah (× 4)	–	295 W (× 3)	$2200	9.3

Sarkar and Ghosh [46] presented a techno-economic analysis of solar powered pumps in Bangladesh. They also provided a list of 108 functioning solar PV pump systems across Bangladesh as an initiative by Infrastructure Development Company Limited (IDCOL). The authors compared PV technology with diesel generators. For a PV system between 0.1 and 20 kW the PV array cost will be US$ 1000/kW, Inverter cost of US$ 500/kW and Battery cost of US$ 300/kW compared to US$ 600/kW for Diesel. For maintenance, the study suggests that the diesel generator system would cost US$ 438/year compared to US$ 80/year for the PV system. The payback period of the PV system was calculated to be 9.33 years producing a benefit to cost ratio of 1.08. The authors have not provided a parallel calculation for the Payback period of a diesel system which may have shown a better comparison, however, a greenhouse gasses (GHG) reduction analysis has been conducted showing that there is a net reduction of 0.865237 t of CO_2 using a PV powered system when compared to diesel system. The GHG analysis however only considers operational emission hence sighting GHG emissions of Solar PV system to be zero.

Gopal et al. [8] conducted a review encompassing different renewable energy source water pumping systems for water pumping including solar PV, solar thermal, wind energy, biomass and hybrid renewable energy systems. The paper describes the limitations of each system and identifies further research that can be undertaken.

With respect to PV technology, a payback period of 6 years was calculated, sustainable for domestic applications up to "medium head" requirements. In drip irrigation applications, it was observed that PV technologies was more effective especially in rural areas, for grassland conversation and small scale irrigation applications. The potential of PV panels to be able to considerably reduce the CO_2 emissions over its 25 years of operation is also envisaged [47].

The main issues that plague PV technology are its affinity to be affected by the intensity of solar radiation, the change in temperature and the velocity of water flow. Energy storage costs are also identified to be very high however, use of a storage tank boosts the performance. One fact the review admits that needs to be addressed is the environmental impact that PV panel manufacture process has, which would be higher for systems using battery for storage. The environmental impact is measured by energy payback time and greenhouse gas emissions. See Table 3.

Table 3
Environmental impact of different types of PV cell types [8].

Type of cell	Energy payback time[a] (years)	Greenhouse Gas emissions (g-CO2-eq./kW h)	Lifetime (years)
Mono crystalline	2.5	50	N/A
Multi crystalline	2.0	43	N/A
Cadmium telluride	1.5	48	20
Copper Indium selenide	2.8	95	20
Amorphous silicon	3.2	34.3	20

[a] Energy payback = energy used for manufacture and set up divided by energy produced.

Cadmium telluride PV cells have been shown to have the best environmental impact with the smallest carbon footprint and payback period in comparison to all solar PV technologies [48] with the highest module efficiency of 19.6% [49]. In comparison PV technology is seen 10 times safer than coal fired plants but 4 times higher in comparison to Nuclear and wind turbine power plants [8]. The average Global warming Potential for 1 kWh of electricity is seen consistently higher as calculated from previous literature is 0.078 $kgCO_2$-eq for PV technology, whereas both Nuclear and Wind produce 0.02 $kgCO_2$-eq [50].

Solar thermal technology, on the other hand, had very less research undertaken and not commercialised due to its low conversion efficiency. Two types of technologies were discussed including, one using vapour power cycles (Rankine Cycle) and the methyl hydride systems. The system efficiencies of vapour powered cycles were very poor ranging from between 0.12% to a maximum of 3% for a 1 m² flat collector aperture area working between heads of 6–15 m pumping between 170 l per day to 1400 l per day with the highest operation values observed for lower heads during the summer using R113 as the working fluid [51].

Water pumping systems using Methyl Hydride could provide higher output at 2000 l per day using a 1 m² solar collector up to 15 m, but even then, the efficiency was 1.5% [52]. The authors establish that due to the low conversion efficiencies, high costs and environmentally unsafe working fluids; solar thermal technologies fall short of PV irrigation technologies.

Gopal et al. identifies that PV, wind and a hybrid system utilising PV and wind will best suit conditions in India when compared with Diesel technologies. Even though the initial investment for PV hybrid is 9 times more than that of Diesel, the Operational and maintenance costs of diesel is 80 times more than that of PV technologies making it economically feasible for the region [8].

4. Solar thermal systems

Solar thermal systems obtain thermal energy from the sun via a solar collector or a solar concentrated surface. The energy is then transferred via a fluid or directly to either a Rankine, Brayton or Stirling Cycle engine which then converts the thermal energy into mechanical work. The mechanical work produced can be used directly to power pumps, converted to electrical energy for storage, or for powering an electrical pump. Fig. 9 shows a schematic of a solar thermal powered irrigation system. Obviously, direct utilisation of the mechanical power is desired, however, storage of thermal energy is a much more difficult proposition when compared to the storage of electrical output.

Most of the research on solar thermal powered irrigation system utilises the Rankine Cycle system or variations of the same. In this system, a working fluid is circulated through a system of boilers, expanders and condenser. The fluid is initially evaporated at the boiler by obtaining heat from a source, in this case solar thermal energy, it then passes through an expansion device (for example a turbine) which generates the power output and then is condensed to complete the cycle [8]. Rankine cycle systems have demonstrated very low thermal efficiencies (around 1%) and high cost associated with initial investment, maintenance and working fluids [9]. Furthermore these systems
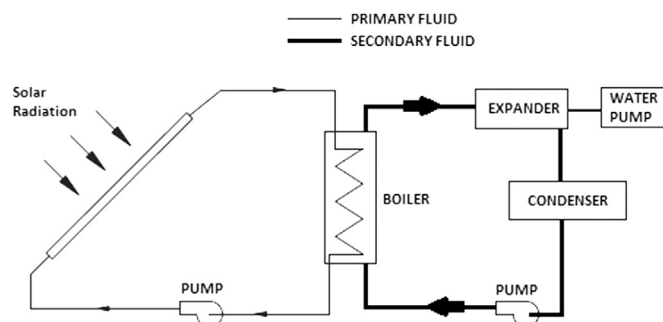
Fig. 9. A typical Rankine cycle solar thermal pumping system [8].

require a significantly larger land space to work with and is very difficult to leakproof the system [8]. These issues have affected solar thermal irrigation research in the recent years, especially as more and more emphasis is being given to the irrigation of smaller farm spaces making this technology unfeasible.

Recently, however, research on medium to low temperature Stirling engines coupled with commercial interest due to the simple construction of Stirling systems has been successful in elevating the technology. Fig. 10. shows a schematic of a Stirling cycle thermal powered irrigation system. A Stirling engine produces mechanical work by utilising cyclic compression and expansion of a working fluid (air, helium, hydrogen, nitrogen) [53] operating at different temperatures and enclosed in a fixed space [54]. The Stirling Engine can achieve the closest efficiency to the ideal Carnot cycle when compared to any other engines [55]. The efficiency of Stirling Engines are calculated to be between 30–40% for maximum operating temperatures up to 923–1073 K at operating rates between 2000 and 4000 rpm [56].

There are three major types of Stirling Engines, α, β and γ type differentiated by it's configuration. The α-type engine has two piston contained in hot and cold cylinders, the β-type engine has 1 cylinder containing a power piston and a diaphragm while the γ-type engine is similar to the β-type engine but houses the power piston separately. γ-type systems have the highest thermal efficiency when compared to the other two systems. Variations of the γ-type engine are the free piston
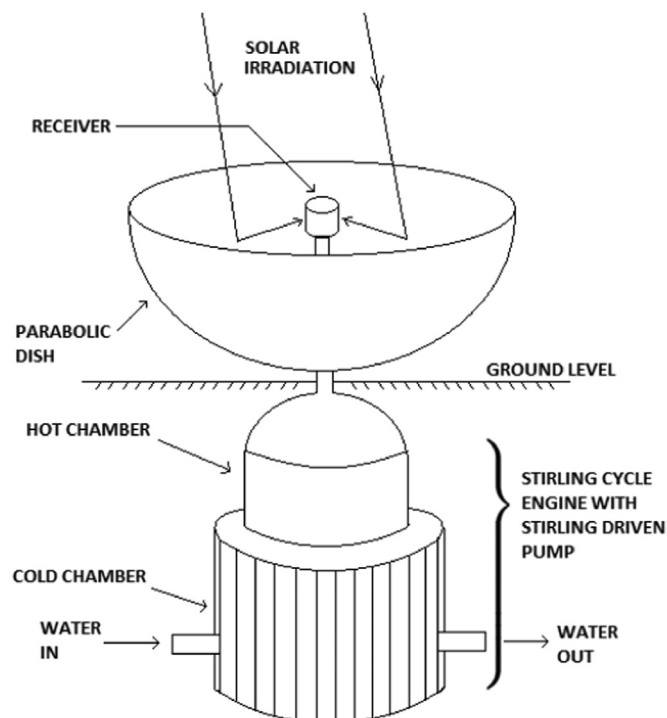

Fig. 10. An example of a Stirling cycle thermal power irrigation system.

engine and the Fluidyne pump [55].

Unlike PV technology, solar thermal technologies for pumping water has not been widely researched in the last 10 years. In fact, no papers were found between 2006 to 2008.

4.1. Solar thermal irrigation technology reviews

Delgado-Torres [57] provided a review of solar thermal heat engines for water pumping. He classified the technologies into two types, conventional and unconventional. Solar energy was first converted into Mechanical energy either by a power cycle or the adsorption/desorption cycle, the mechanical energy was then either converted into electrical energy to be used for a conventional pump or used directly with an unconventional pump design. Among the conventional methods, the Rankine cycle systems were discussed. Rankine systems generally used water as the working fluid, but as time went on various other fluids were used either on their own or sometimes in conjunction. The working fluids tested included, water, sulphur dioxide, ether, chlorobenzene, R11, R113 and HT-43. Flat plate and parabolic collectors were the preferred collector systems as per the research undertaken, however there was also research undertaken on conical reflectors, truncated cones, and wooden boxes with reflector plates.

The largest Parabolic trough collector project was in Egypt in 1913 that used a 60 m long and 4 m wide parabolic trough to pump 27 m^3/min and delivered 40.42 kW maximum power output [58]. In 1976, in Mexico, a flat plate collector spanning about 2.5 ha included a vapour powered turbine that was used to generate electricity to produce 1000 m^3/day [59]. The largest parabolic dish installation was made in India in 1987 that used 6 collectors with 9 m diameter each to produce steam at 500 °C at 7 MPa to drive a steam engine rated at 20 kW which was then connected to an irrigation system [60]. The wooden box with reflector plates was also an interesting project, that spanned over 1000 m^2 (1 ha) land area and produced a mean daily power output between 10.29–11.76 kW and a maximum power output of 17.64–23.52 kW generating a discharge of 11.3–12 m^3/min across a head of 10 m [58]. Among the smaller systems, included a truncated cone with 10 m diameter at the top and 4.5 m diameter at the bottom which could provide 7.35 kW driving a pump to discharge at 6.4 m^3/min of power by generating steam at 1.03 MPa from a 5 m depth [58].

Most of the conventional systems discussed were too large in size and required a big financial investment. Moreover, the Rankine systems is very complex and would require a lot of maintenance dealing with intricate pipe work, boiler and turbines. The author discussed three distinct alternative methods that could be used to make the technology viable for small scale use. Among the unconventional methods for water pumping, the author discusses three distinct categories which are, vapour cycle systems, liquid piston systems and metal hydride systems. Vapour cycle systems use a simple displacement pump with the water being displaced by steam/ethyl/pentane vapour. A 1 m^2 area flat plate solar collector using such a vapour cycle was able to provide a flow of 336 l/day at 6 m head, 250 l/day at 8 m head and 17 l/day at 10 m head [61].

Liquid pistons is a variation of free piston Stirling engines in which the solid pistons is replaced with liquid to allow lower levels of friction and air tightness, see Fig. 11. The Fluidyne pump is an example of such a system where air is heated and cooled and causes a U-shape liquid column to oscillate and thus cause lifting and suction. In the laboratory, the Fluidyne systems have been able to provide up to 3 kW of power at a temperature difference of 95 °C and pressure of 160kPa and giving 2 m^3/h pump capacity [62].

The final unconventional method discussed in the paper was using the metal hydride. In this system, metal hydride is subjected to heat causing release of hydrogen, as hydrogen is released the pressure is increased pressing down on the piston. Once the piston reaches the bottom of the cylinder, the metal hydride is then cooled, lowering the pressure and leading to the absorption of hydrogen. The system studied
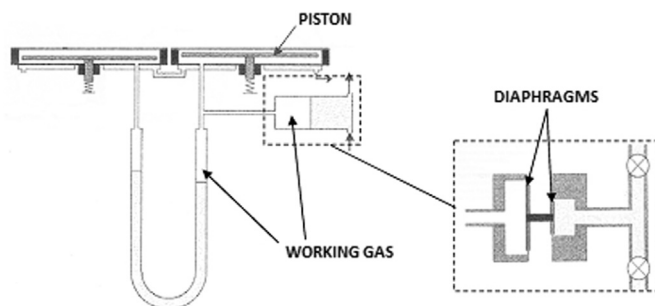
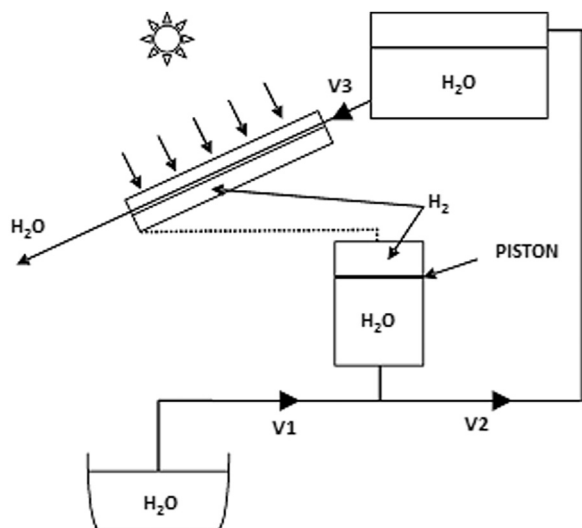Fig. 11. Liquid Piston pump design using diaphragms [57].

Fig. 12. Metal hydride based solar thermal water pumping system design [52].

Table 4
Range of temperature and ratio of concentration of various solar thermal systems [64].

Technology	T [°C]	Concentration ratio	Tracking type
Air Collector	0–50	1	–
Pool Collector	0–50	1	–
Reflector Collector	50–90	–	–
Solar Pond	70–90	1	–
Solar Chimney	20–80	1	–
Flat Plate collector	30–100	1	–
Advanced Flat Plate Collector	80–150	1	–
Combined heat and power solar Collector	80–150	8–80	1-axis
Evacuated Tube Collector	90–200	1	–
Compound parabolic collector	70–240	1–5	–
Linear Fresnel Reflector	100–400	8–80	1-axis
Parabolic trough	70–400	8–80	1-axis
Heliostat field + Central Receiver	500–800	600–1000	2-axis
Dish Concentrators	500–1200	800–8000	2-axis

worked on the basis of heating and cooling of the metal hydride that could be controlled by a flat plate collector and the water flow generated by the pumping process respectively. A test on a metal hydride system was conducted in Kolkata in 2004 using a 1 m² flat collector at a tilt angle of 15°. On a clear day, a maximum of 2000 l of water was pumped to a height of 15 m and on a cloudy day 500 l of water was pumped. In terms of metal hydride use, on a clear day 240 l/day/kg of metal hydride is used while on a cloudy day it is about 60 l/day/kg [52]. The set-up of the system is shown in Fig. 12.

The issue with unconventional systems is that the power output of the systems is much lower than those systems using the conventional methods. Added to this the operational costs of metal hydride systems is high as well. However, unconventional systems have the advantage of being used in difficult to access rural areas and the relatively smaller scale systems. This could allow even small scale farmers can benefit from a feasible and viable technology. The classification of conventional and unconventional technologies as established by Delgado-Torrez shall be followed in this paper.

4.2. Conventional solar thermal technologies

Lakew et al. [63] conducted a thermodynamic analysis of a low temperature (60 °C) heat source Rankine cycle functioning in conjunction with a thermal driven pump with supercritical carbon dioxide as the working fluid. A shell and tube heat exchanger (diameter = 5 mm) functioned as the thermal pump removing the need of a mechanical driven pump and thus reducing the maintenance. A continuous source of heat was required for this system. The study showed that a Rankine cycle operating with a thermal driven pump had higher power generation capability than conventional Rankine cycle but an additional low temperature heat source was required for this process.

Hence in this method, there was a requirement for a heat source for the boiler (100 °C) as well as a heat source (60 °C) for the pump. While the heat source for the boiler was the same in both the thermal pump driven Rankin cycle and the mechanical pump driven Rankine cycle, the thermal pump did not require maintenance, had lower noise levels and vibration and maintained a lower rate of efficiency deterioration when compared to mechanical pumps. However, in terms of cost it was more expensive due to the requirement of heat exchangers.

Tchanche et al. [64] reviewed the various applications of using organic Rankine cycles for generating power from low-grade heat. The study considers co-generation systems, water heat recovery systems, desalination systems as well as solar thermal power systems. Organic Rankine cycles utilised refrigerants and hydrocarbons as the working fluid instead of water as Rankine cycles using water were more complex and utilised expensive turbines which are also at high risk of erosion. Furthermore, water needs to be superheated so that during expansion the water does not condense which in turn means there is excess pressure in the evaporator. The authors listed the temperature ranges and concentration ratios of different collector systems as per Table 4. Dish concentrators provided the highest temperatures with the least footprint. Without a tracking system Evacuated tube collectors and parabolic collectors are shown to have the highest concentration ratios.

One of the more comprehensive systems discussed in the study included an Organic Rankine Cycle system consisting of a 60 kW propane boiler, compact brazed heat exchanger, air compressed diaphragm pump, radial flow turbine at 65,000 rpm and a high-speed actuator working at relatively low temperatures between 93 °C in the inlet (81 °C at the evaporator) and 38 °C at the condenser with n-Pentane as the working fluid producing a mass flowrate of 0.1 kg/s, power output of 1.44 kWe and costing US $25,880 with 37% of the cost attributed to the cost of the turbine-generator [65]. The other systems discussed, used different mid to high range collector systems and tested various types of working fluids. Hybrid systems with collectors and gas/diesel burner systems were also considered.

Solar Ponds were also discussed with large to medium size power plants shown to be constructed and operated in Israel, Australia and the USA. Systems working on the principal of Organic Rankine Cycle for pumping of water for desalination and distribution were also studied but the size of these systems were large for consideration for small scale irrigation.

Low grade conversion systems investigated in this paper were investigated specifically for ocean thermal energy conversion to function offshore at low temperatures and function as a total resource
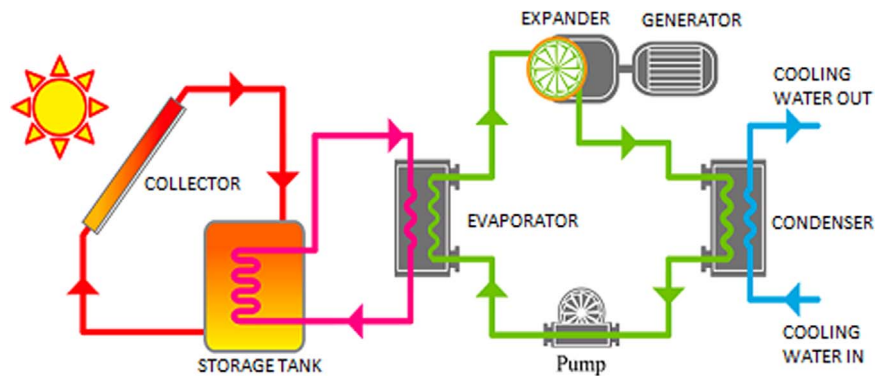
Fig. 13. Solar powered organic Rankine cycle system [66].

system. These systems are good for off the grid power solutions for remote areas, however, the size and costs associated with the systems will be viable only if the technology is implemented on a community level and not individual level.

Baral et al. [66] performed a thermo-economic analysis and experimentation of a small-scale organic Rankine cycle system that was powered by solar energy for power generation in rural areas. The power output from the designed system ranged between 400 W and 1.38 kW during the year with the maximum output in April. The system is a typical organic Rankine cycle system using refrigerant R245fa as the working fluid and 15 evacuated tube solar collectors would provide hot water 90 °C to 120 °C. see Fig. 13. The selling cost for the technology was found to be US$ 0.68 and at that price the payback period is 19 years for operational components most of which have a life time of 20 years. This has been calculated as per the prototype tested, however, a subsidised development programme can assist in fine tuning the technology and thus reducing the cost of the technology. Even then, the technology would not be suitable for independent small scale farmers.

Baral and Kim [67] analysed the economic viability of a standalone organic Rankine cycle system that functions on solar thermal energy to pump water for drip irrigation in rural Nepalese area. The authors performed experiments based on a prototype and analysed the economic viability of the system based on the solar radiation data described in Fig. 13. Economic assessments were carried out for 1 kW and 5 kW systems and the cost of hot water (at 40 °C) was shown to be between US$ 1.86/m^3 and US$ 2.47/m^3 for a 1 kW system and 150 m pumping head pumping 2190 m^3 per year, while the 5 kW system pumped 11,100 m^3 per year. Increasing the size of the system and decreasing the pumping head was shown to reduce the cost generating a profit index of 1.6 with a payback period of 8 years at the above costs of selling water. Such a system is viable for a rural community service but not for independent small scale farmers.

Moonsri et al. [68] designed a thermal water pump functioning on hybrid energy input for pumping water from a shallow well to produce hot water in Thailand. The systems consisted of a 2.1 m^2 solar collector at an inclination of 14° made of copper plates and tubes and a 2000 W electric heater to work in conjunction with the solar collector to produce steam coupled with a system described in Fig. 17 based on research conducted by Sitranon et al. [69]. The system could pump 215 l of water up to 3 m height working on 6.5 MJ of power from the hybrid system. The study compares the system with a solar PV powered system. Though the comparison was not conclusive, it identifies various maintenance issues with the hybrid system including the erosion of rubber seals, valves and heat loss. PV systems disadvantages are highlighted in terms of performance loss at high temperatures, expensive battery and the environmental impact of producing PV panels.

Bataineh [70] investigated the performance of a water pumping systems powered by solar thermal energy. Recent developments in

solar thermal systems were also presented and methodologies to further enhance the energy conversion were proposed. Set in Jordan, a system working on the principal of the Rankine cycle in conjunction with parabolic trough collector was studied using mathematically simulate models. Considering a 526 m^2 collector area, producing 30 kW energy, 20 years of operational life of the system, 6% maintenance cost per year, US$ 250/m^2 being the cost of the solar field and US$ 60,000 the cost of the steam turbines, the cost of solar energy amounts to US$ 0.075/kWh which in comparison to diesel is 0.082/kWh. While the technology is more cost effective than diesel generated, it is still more expensive than PV and requires a large area. The investment cost is also very high making it unsuitable for rural areas.

4.3. Unconventional solar thermal technologies

Mahkamov and Orda [62] performed a preliminary analysis of the working process of solar thermal water pumps designed similar to a free-piston Stirling Engine. The system uses a fluid piston that claims to overcome issues of instability that were faced by conventional fluid piston pumps by including a new diaphragm setting and reducing the dead space in the hot cylinder, cold cylinder and regenerator. They discussed in their paper that solar thermal water pumps were low maintenance and low cost systems that could provide pumping capacities of 0.2–1 m^3/h and a dynamic head of 1.5–5 m with an air-steam mixture as the working fluid. The study proposed a mathematical model to simulate the internal processes associated with liquid piston engine. The mathematical model was then compared with a laboratory prototype and the parameters were mostly within 5–10% of the predicted models but compressor volume was recorded over 20% higher than that predicted.

Kurhe et al. [71] designed a heat engine using organic working fluid (acetone) to provide 20 L/h of water per stroke and an operating head of 5 m. The thermal water pump cycle functioned at a working temperature of 85 °C to produce a system efficiency of 0.25–0.5%. The engine used a chemical inert membrane that was displaced due to the pressure developed by the working fluid to pump water. The pressure of the working fluid was regulated using a heat exchanger where hot and cold water was pumped into the evaporate and condense the working fluid respectively. See Fig. 14. The efficiency of the system was low due the loss of heat through the membrane at the water interface. The need for work input necessitates the use of a separate power source.

Jokar and Tavakolpour-Saleh [72] introduced a novel active low temperature differential pump that is powered predominantly by solar thermal energy and operates on the basis of the Stirling cycle. The proposed system works with a liquid piston to provide effective sealing while reducing friction generally associated with solid power pistons and the cylinder encasing the piston. A flat plate solar collector with a reflecting surface is the heat source while the heat sink is a water-cooled surface and air is the working fluid in the main chamber that
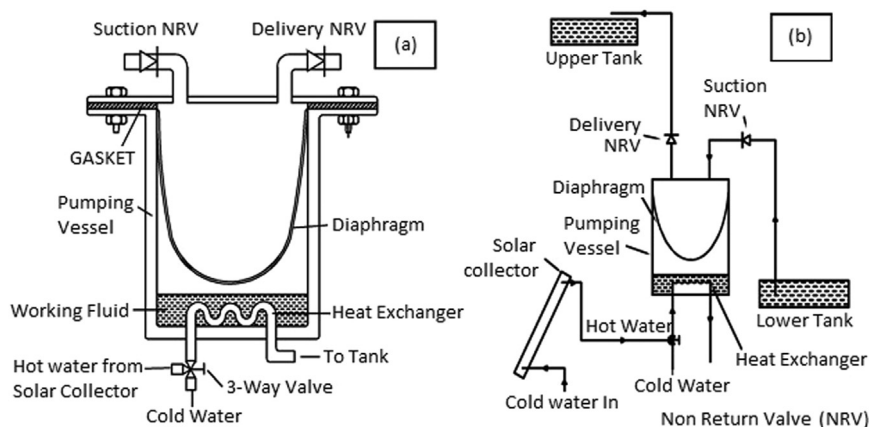
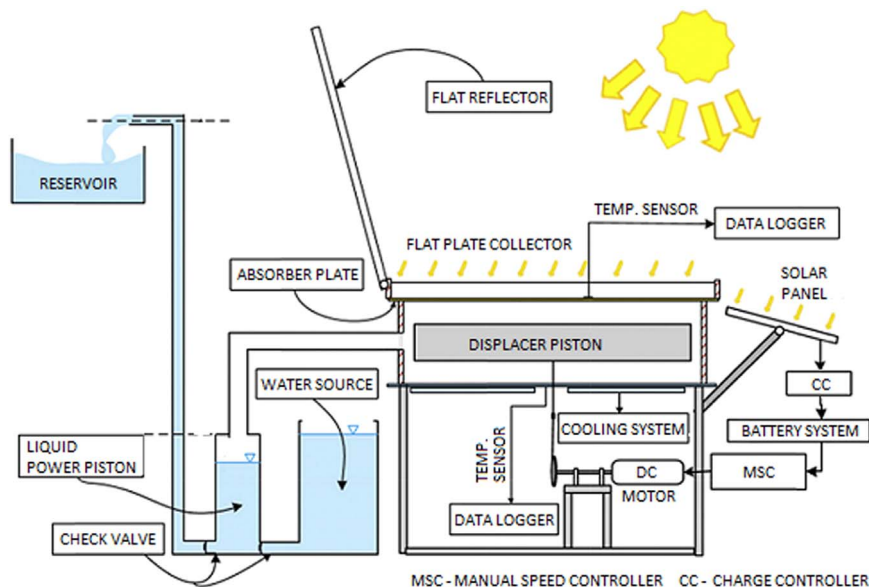**Fig. 14.** (a) Pumping vessel assembly (b) Full system schematic [71].

Fig. 15. Solar powered low temperature differential stirling pump [72].

houses a displacer. A DC motor powered by a small battery and PV system controls the motion of the displacer piston to allow for adjustment of the working frequency to account for the pressure variation of the working fluid. For more controlled system, pressurised helium is recommended as a working fluid. The PV system also assists in initiating the displacer piston, as displayed in Fig. 15.

A mathematical model was prepared and compared with small scale experimental results with the model results closely matching the experimental data. This is a novel idea of assisting the displacer piston, however, using the PV module and battery makes it very expensive.

Date and Akbarzadeh [73] conducted a theoretical study of a water pumping system powered by a solar pond and implementing a novel thermodynamic power cycle. The study proposed the system as an alternative to electrical pumps used in salt farms, that works at a temperature difference of 60 ℃ and acetone as the working fluid. The study introduced a two-stroke thermal powered pump cycle that extracts the work at the same time the working fluid is evaporated at a constant temperature while during the condensation the water that is being pumped adds the work on the working fluid.

The study proposes a hybrid system where the pump is thermally powered and all the auxiliary power for sensors, valves and the working fluid pump comes from a battery and PV system. The condenser and heat exchangers are contained within the solar pond system, as shown in Fig. 16. The analysis proposes that at 10% heat extraction of the annual average global solar radiation, a head of 22 m can be anticipated for operation up to 338 days of the year pumping 0.53 m³ of water per m² of solar pond area per day. The research goes on to establish that with a floor area of 5200 m² of solar pond 2800 m³/day of salt water could be pumped from depths between 2–10 m. For this, a 20 L stroke volume will be required in conjunction with 0.01 m² heat exchanger and 0.1 m² condenser.

The thermal pump proposed can theoretically replace electrical pumps, however, the costs and practicality associated with the technology required experimentation work and further study.

Sitranon et al. [69] conducted a parametric study of the suction head assembly of a thermal water pump with steam as the working fluid and discussed its applications. The study analysed the amount of air that is required to be added to the steam working fluid and looked to shorten the cooling time by employing direct contact cooling. A 2-stroke liquid piston powered by an electrical heater was used to provide consistent heat source to the heating tank to transfer water from a well to a storage tank, as shown in Fig. 17. The study suggests that using air in conjunction with steam as the working fluid will lower the working temperature and thus make it more suitable for solar thermal use. Tests were conducted in Thailand and the results matched that of the simulation model used. At a temperature difference of about 60 ℃, 123.9 L of water was pumped requiring 19.73 MJ of energy to provide a mean suction head of 6 m and a discharge head of 1 m.
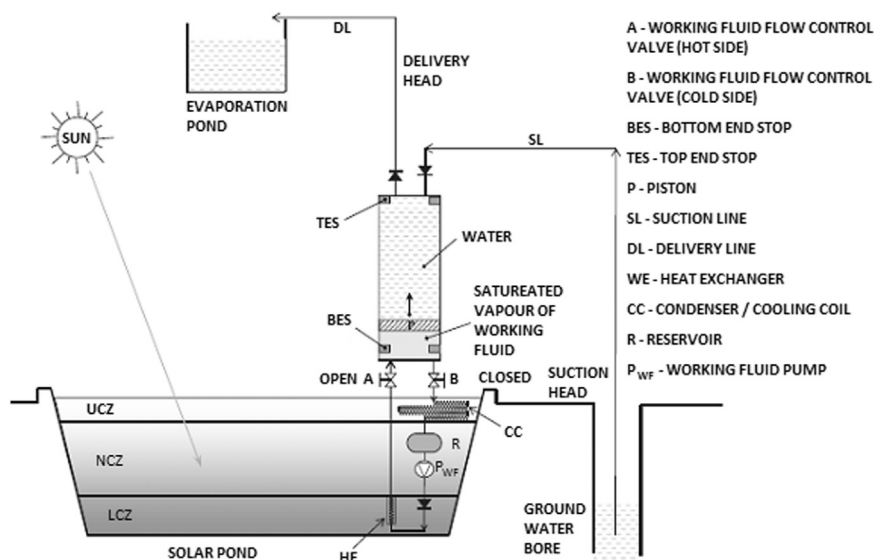
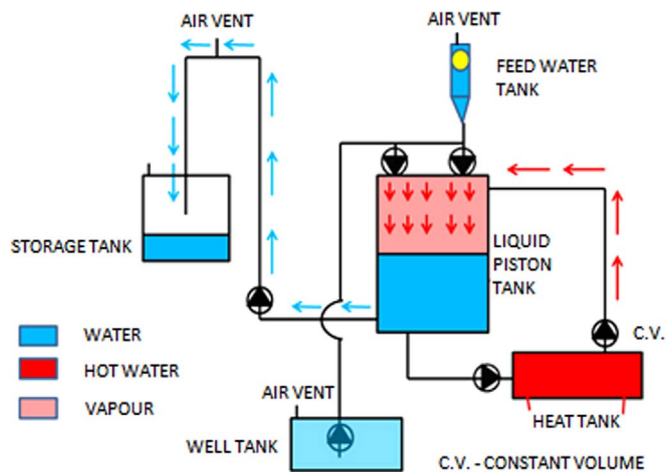**Fig. 16.** Solar pond in conjunction with a two-stroke thermal water pump [73].

Fig. 17. 2-stroke liquid piston pump [69].

5. Results and discussion

In the current state, PV systems are far more viable in comparison to solar thermal systems especially as small-scale farming solutions in the technological sense. Assisted further by the drop of cost of solar cells, seamless integration with available technology, reduction in price of Lithium Ion batteries and rapid commercialisation of the technology. In this section, a summary of the advantages and disadvantages of the systems are presented in the context of small scale irrigation in the remote and rural areas of Sub-Saharan African region.

5.1. PV technology

The data from the reviews have been compiled and presented as per tabularised in Table 5. The Table focuses on the irrigation requirement of the system (including flowrate and pumping head), The PV module and power of the system utilised to meet the requirement, the area of the farm land and the cost of the technology.

The cost of PV technology is often compared to diesel powered systems. There is a clear advantage of PV systems over diesel powered systems in terms of the life time cost analysis, however, the initial investment for PV systems is much higher than diesel powered systems especially with regards to operational and maintenance costs. In comparison to other renewable energy systems such as wind and solar

thermal systems reviewed, the investment cost is lower. Even then, a well-designed solar PV system can have a payback period of under 6 years, which so far is unmatched by other types of irrigation solutions in remote rural areas.

In terms of efficiency, the most efficient PV panels include the multi-Junction five-junction cells with 38.8 ± 1.2% efficiency. However, the environmental impact of these cells is very high. Cadmium telluride (CdTe) cells with conversion efficiency of 21.0 ± 0.4% and a module efficiency of 19.1%, has the least impact on the environment. CdTe cells produce the least amount of greenhouse gas emissions and have quickest payback period in comparison to all other solar PV technologies [8,11].

DC motors are the preferred choice of motors for solar power systems less than 5 kW capacity. The maximum requirement for solar power to irrigate 1 ha land is less than 1 kW as per estimates by R. López-Luque et al. [25] Hence for a small scale rural operation DC motors will be the better fit when compared to AC motors. DC motors with permanent magnet provide the highest torque, fastest response and the highest efficiency among DC motor systems. Permanent magnet DC motor in conjunction with diaphragm pump or positive displacement pumps show the highest pumping system efficiencies of 70%, with positive displacement pumps doing better for higher heads and diaphragm pumps performing better for lower heads.

There are conflicting studies with regards to cost of PV system with and without the incorporation of battery systems. Some studies suggest that a simple overhead water tank may be enough while others argue that incorporating a battery system will reduce the size of solar panels required and provide the possibility of on demand energy use. O. Deveci et al. [22] for instance designed a 132 Wh/day system in Turkey with just two PV panels 10 W each to power a battery which was enough to power a pumping system to irrigate 1 ha of land daily for 2 h for US$ 582, while an equivalent non-battery powered system would cost 2.75 times more. Similar research in Thailand by K. Treephak et al. [45] however, disagrees sighting the cost of DC motor system without battery to be the most cost effective system for the irrigation of 1.6 acres of land having a payback period of 7 years (estimated cost US$ 2000/ha) as compared to 9.3 (estimated cost US$ 2200 ha) years for an equivalent system using battery. AC motor systems on the other hand were more expensive having a payback period of over 10 years with or without battery. Research by D. H. Muhsen et al. [7] has also shown that using aluminium foil as a reflective surface can be set-up to boost the irradiation during cloudy weather or when there is less irradiation.

Table 5
Review summary of Solar PV water pumping.

Author	Location	Function	Flowrate	Head	PV panels	Power out avg	Battery	Farm size	Cost
Deveci [22]	Turkey	Trees 2 h irrigation	610 l/h	1 m	2 × 10 Wp	132 Wh	Yes	–	$582 Investment
Campana [43]	Mongolia China	Alfaalfa	50 m³/ha	40 m (TDH)	–	2.9 kWp	–	–	min - $0.8/Wp max - $2.0/Wp
Campana [24]	Mongolia China	Alfaalfa	3.9 m³/h	5 m	6 × 0.96 kWp	–	–	–	$2/Wp
López-Luque [25]	Almeira Spain	Olive Trees	2 m³/h	40 m 60 m 80 m	–	150 W/ha 250 W/ha 300 W/ha	–	250 trees /ha	$2.14/Wp
Chandel [10]	–	Orchard	3.4–3.8 l/h	–	–	900 Wp	–	–	–
	Madina Saudi Arabia	–	22 m³/day	–	24 Modules 8 series 3 parallel	–	–	–	–
	Gunung-kidul India	water Supply	0.4–0.9 l/s	1400 m	32 PV Panels	3200 Wp	–	–	–
	Spain	Orchard	161 m³/day	–	–	6 kWp	–	10 ha	–
	Algeria	–	60 m³/day	14.5 m	–	–	–	–	$0.04 /m³
Chandel [30,74]	Himachal Pradesh India	Test	5500 l/h 4929 l/d[a]	–	12 mono-C-Si PV modules	396 Wp 235 Wp[a]	Yes	–	–
Kumar [27]	Hyderabad India	–	900 l/h	4.5 m	1.44 m²	148 W	Yes	2 ha	$410 (full system)
Hossain [26]	Dhaka Bangladesh	Brinjal Tomato Wheat Rice	100 l/min	33.5 m	1050 Panels with tracking	1440 W	Yes	520 m² 520 m² 496 m² 220 m²	$5660
Bengh-anem [75]	Saudi Arabia	Test	–	50–80 m	PV array of 24 mono crystalline solar cells (8S × 3P)	1800 Wp	No	–	–
Treephak [45]	Thailand	Rice	15 m³/h	3.9 m	250 W × 6 - AC 250 W × 4 - DC 295 W × 4 - AC 295 W × 3 - DC	1500 W 1000 W 1180 W 885 W	No No Yes Yes	0.5 ha 0.5 ha 0.5 ha 0.5 ha	$2800 $2000 $2800 $2200
Yahyaoui [31]	Brazil	Tomato	200 m³/h	–	–	10–10,000 W	Yes	10 ha	–
Reca [29]	Almeira Spain	Tomato	60,000 l/h	40 m	–	600 W/ha	No	1.9 ha	$2.14 /Wp
Jones [34]	Jordan	Desalination	4000–15,000 m³/ha/yr	25–100 m	–	245 W	Yes	4–10 ha	$1.25-$4.30 /W
Sontake [9]	Nigeria	–	20 m³/day	–	60 WP × 28	–	Yes	–	–
	Germany	Portable water	–	5–125 m	90 nos	180 kWp	–	–	–
	Bushland Texas	–	2–8 l/min	3–70 m	–	160 W	–	–	–
	–	–	10–165 l/h	10–16 m	2 × 45 W	–	–	–	–
	–	–	40 m³/day	10 m	–	300–500 Wp	–	–	–
Setiawan et al. [23]	Indone-sia	Portable Water	0.2–0.9 l/s	218 m	32 × 100 Wp	3200 Wp	no	–	–
Muhsen [7]	Saudi Arabia	–	600 l/h	50 m	–	0.98 kWp	–	–	–
	Egypt	–	150 m³/day	30	–	6.048 kWp	–	–	–
	Algeria	–	6 m³/day	–	(4S × 3P), (3S × 4P) BP Saturn	–	–	–	–
	Kairouan Tunisia	–	6.5–30 m³/day	65–112 m	–	2.1 kWp	–	–	–
	Ghardaia Algeria	–	4–6 m³/day	19–35 m	–	–	–	–	–
	Madina Saudi Arabia	–	< 22 m³/day	80 m	(6S × 3P), (12S × 2P), (8S × 3P), (6S × 4P) × 75 Wp	–	–	–	–
	Oran Algeria	–	6–65 l/m	0.6 –11 m	–	1.5 kWp	–	–	–
	Tall Hassan Jordan	–	45 m³/day	105 m	–	5.9 kWp	–	–	–
	Greece	–	20 m³/day	30 m	(2S × 6P) × 51 Wp	–	–	–	–
	Turkey	–	18 m³/day 52 m³/day	20 m	2 × 230 Wp 8 × 200 Wp	–	–	–	–
	New Delhi India	–	38 m³/day	5 m	4S × 5P	–	–	–	–
	Purwodad Indonesia	–	1.44–3.24 m³/h	218.34 m	8S × 4P	3.2 kWp	–	–	–
	Louata Tunisia	–	7.7–14.7 m³/day	65 m	14S × 3P	2.1 kWp	–	–	–
	Madina Saudi Arabia	–	≤ 33 m³/day	50–80 m	8S × 3P	1.8 kWp	–	–	–
	Bejaia	–	43.66–	11 m	6S × 3P	990 Wp	–	–	–

Table 5 (continued)

Author	Location	Function	Flowrate	Head	PV panels	Power out avg	Battery	Farm size	Cost
	Algeria		27.91 l/min						
	Nigeria	–	10–30 m³/day	40 m	–	840–2520 Wp	–	–	–
Tiwari and Kalamkar [76]	India	Domestic Use	20,232 L/d		3S ×2P	850	No	–	–
			23,317 L/d		4S × 2P	1000			
			24,374 L/d		5S × 2P	1020			
			22,130 L/d		7S	1040			
Kabalci [77]	Turkey	Vineyard	400 m³/d	100 m	245 Wp Panels connected ((2P) × S) × 2	2000 Wp	Yes	–	–
Sarkar [46]	Bangladesh	Farm land[b]	128 m³/d	12.8 m	Poly-crystalline Si	3.5 kW	Yes	–	$ 1800/kW
			373 m³/d	9.71 m		4 kW			
			740 m³/d	16 m		7.5 kW			
			645 m³/d	14.6 m		11 kW			
			300 m³/d	35 m		7.5 kW			

[a] Values recorded after 28 years of exposure. Initial value based on capacity.

[b] Only the Lowest and Highest values have been identified in the table out of 108 installations.

Several other studies quote varying values of power output and costs, hence, the conclusion from these studies is that the best way to optimise the cost and design of the PV powered system is to understand the requirements of the crop and perform extensive site survey to analyse the working conditions of the system. The more data available the more efficient the design of the system and thus lower the costs. It is often due to the lack of data that PV systems costs increase as more complex and intelligent systems are integrated into the system. One of the major reasons for the use of the battery is the functionality of the pump. Inconsistent irradiation and thus power output from the PV panels may vary restricting the time of operation of the pumps.

Based on the literature reviews, and considering the case for drip irrigation, the simplest, most cost effective solar PV system is one consisting of cadmium telluride PV module at 19.5% efficiency. The panel combines with a permanent magnet DC motor driven pumps (positive displacement pump for higher heads or diaphragm pump for lower heads) capable of providing 70% pump system efficiency. Using a storage tank instead of battery, this system provides an overall theoretical system efficiency of 13.65%, as shown in Fig. 18. The system will function when solar radiation is available and water from the storage tank can be used for drip irrigational purposes.

That brings us to the drawbacks of the PV technology, one of the major issues with Solar PV technologies is the degradation of power of PV cells due to long term exposure. Generally, the degradation is measured to be 0.8% per year as per climatic conditions in India [30], however, elevated temperatures and humidity in Sub-Saharan Africa may pose further challenge to PV technology. The issue here is that, it is a parameter that has not been extensively studied, hence in pursuit to compensate for the loss of degradation more intelligent systems (such as ANN, MPPT and Fuzzy Logic based controllers) may have to be incorporated and that will drive the cost up. Furthermore, any maintenance or modifications of the system will be expensive if

resources such as replacement cells are not readily available in the region in case of shipping or operational misuse.

Implementing PV technology is costly enough for Farmers. Weak knowledge-exchange and lack of incentives further creates further difficulty for innovative practices [78].

While PV technology is 10 times less harmful to the environment than coal it is still 4 times more harmful than Nuclear and wind turbine power plants [8,50]. Furthermore, the carbon footprint of transportation is also required to be considered for the Sub-Saharan African region as PV panels are not produced in this region.

Accumulation of dust on the Panels, overheating during energy conversion and functioning at higher temperatures are some of the other main issues associated with the reduction of performance of solar panels.

5.2. Solar thermal technologies

The data from the reviews of solar thermal technologies have been compiled and presented as per tabularised in Table 6. The data focuses on the irrigation attributes of the system including flowrate and pumping head, the thermal system and power output of the system utilised for irrigation and the cost of the technology. The reviews and data reveal a lack of real life testing to solar thermal technologies hence farm size data is not available for solar thermal technologies for comparison with PV technologies.

Solar thermal powered water pumping technologies can be categorised into two types, conventional pumps and unconventional. Conventional Technologies generally utilise the Rankine Cycle whereas unconventional systems make us of the vapour cycle, metal hydride systems or liquid pistons. Conventional systems are shown to produce more power in comparison to unconventional systems however, conventional systems are generally very large and complex. Because of this and the low efficiency the conventional systems do not pose to be an effective solution. Unconventional technologies on the other hand generally pose lower pumping potential or in the case of Metal hydride solutions, pose high costs.

The most compact type of solar concentrators are dish concentrators which in conjunction with a double axis tracking mechanism can provide up to 1200 °C which is also on the high cost side. At low costs the options include the flat plate / reflector collectors capable to provide up to 100 °C temperatures. In the median Liner Fresnal collectors provide both a low cost and high temperature potential of up to 400 °C. The most frequently used collector technology however is the Parabolic trough collectors shown in the studies capable of providing temperatures up to 500 °C with a single axis tracking mechanism [64].

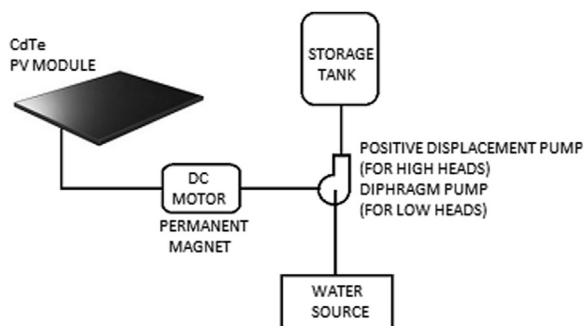The organic Rankine cycle systems are the most common form of

Fig. 18. Schematic of the most effective Solar PV water pumping system for remote rural areas based on literature reviews.

Table 6
Review summary of solar thermal water pumping technology.

Author	Location	Flowrate	Head	Power cycle	Collector type	Temp difference (°C)	Power out avg	Cost
Mahkamov [62]	UK	–	–	Stirling	–	70–35	20–40 W	–
Delgado- Torrez [57]	Paris France	2.2 m^3/h	–	Rankine	Conical Reflector	–	–	–
	Paris France	7 l/min	3 m	Rankine	Parabolic 9.2 m^2	–	–	–
	Pasadena US	5.3 m^3/min	3.6 m	Rankine	Truncated cone 10 m dia top 4.5 m dia bottom	–	7.35	–
	–	–	–	Rankine	Flat Plate	–	14.7 kW	–
	Pensilvania US	–	–	Rankine	Solar Pond 11,200 m^2	–	2.57	–
	Pensilvania US	11.3–12 m^3/min	10 m	Rankine	Wooden Boxes 1000 m^2	–	10.29–11.76 kW	–
	Meadi Egypt	27 m^3/min	–	Rankine	Parabolic Trough 60 m × 4 m	–	40.42 kW	–
	Mali Africa	11.3 m^3/day	45.7 m	Rankine	–	–	–	–
	–	–	4.8 m	Ericsson	Parabolic	–	–	–
	Arizona US	38 m^3/min	–	Rankine	Parabolic 554 m^2	–	–	–
	New Mexico US	2.6 m^3/min	34 m	Rankine	Parabolic 622.4 m^2	–	–	–
	Guanajuato Mexico	1000 m^3/day	–	Rankine	Flat Plate 2499 m^2	–	–	–
	Dakar Senegal	8–10 l/min	13–14 m	Rankine	Flat Plate 6 m^2	–	–	–
	San Luis Mexico	2.5 m^3/day	–	–	–	–	25 kW	–
	Various	30 m^3/day	20	–	Flat Plate 100 m^2	–	–	–
	Mexico	–	–	Rankine	Parabolic Trough	–	1 kW	–
	Arizona US	–	–	Rankine	Parabolic Trough 2140 m^2	–	–	–
	Egypt	–	–	Rankine	Flat Plate 384 m^2	–	10 kW	–
	–	14.61 l/min	3 m	Rankine	4 × Flat Plate 1 m^2 each	–	–	–
	India	6.5 m^3/day	11.2 m	Rankine	Flat Plate 7 m^2	–	–	–
Delgado- Torrez [57]	India	–	–	Rankine	6 × Parabolic 9 m dia	–	20 kW (500 °C Steam)	–
	Iran	20 m^3/day	–	Rankine	Flat Plate	–	–	–
	India	2 m^3/day	6 m	Organic Rankine	Parabolic	–	–	–
	UK	0.5–2 m^3/h	–	Liquid Piston	–	MAX Temp: 95	0.8–3 kW	–
	Kolkata India	240 l/day	15 m	Metal Hydride	Flat Plate 1 m^2	22–62	–	–
Lakew [63]	–	–	–	Rankine	–	80 (plus 60 °C Low level heat source	2800–3750 kW	–
Tchanche [64]	UK	–	–	Organic Rankine	–	55	1.47 kW	$ 30,000
	Sendai Japan	0.016 kg/s	–	–	–	–	350 W	–
Date [73]	Australia	140 m^3/day	35 m	2-Stroke Liquid Piston	Solar Pond 5200 m^2	–	–	–
Kurhe [71]	India	20 L/h	5 m	2-Stroke Diaphragm pump	Flat plate Collector	50–60	–	–
Baral [66]	Busan South Korea	–	–	Organic Rankine	Evacuated Tubes	65–95	0.4 kW–1.38 kW	$ 25,800
Jokar [72]	Iran	0.125 l/s	1.5 m	Stirling	Flat Plate Reflector 2×1 m	100	1–2 W	–
Baral [67]	Nepal	2190–11100 m^3/year	150 m	Organic Rankine	Evacuated Tubes 150–200 m^2	60–100	1–5 kW	$13,000 (1 kW) $66,900 (5 kW)
Sitranon [69]	Thailand	60–95 l/h	2–6 m	Liquid Piston	–	70	–	–
Moonsri [68]	Thailand	192.2–218.8 l/day	1–5 m	Liquid Piston	Flat Plate	42.9–46.7	–	–
Bataineh [70]	Jordan	–	–	Rankine	Parabolic Trough 526 m^2	–	30 kW	$0.075/kWh

concentrated solar thermal power generation system utilised for irrigation. These systems are generally multi facet as they would be highly inefficient for the sole purpose for irrigation. Most systems with this technology undertakes irrigation in conjunction with either desalination or rural power generation. Small systems are shown to generate between 1.5 kW power with a payback period of 20 years, while larger systems are capable of a maximum 40 kW to provide a pumping capacity of 27 m³/min. These systems may be favourable for investment by a group of farmers in a village. However, as a standalone system it is very large and immobile in comparison to PV panels while the investment costs are similar.

Stirling cycle systems are also used for irrigational purposes. These systems generate lower power; however, they are compact and are easy to manufacture. The Stirling cycle based technology systems are investigated mostly to reduce the cost, thus the research undertaken investigated medium to low power solar collection / temperatures with a difference of 60–95 °C. Higher temperatures should be able to provide better outputs. The systems investigated in this paper provide relatively low head losses and flows; however, provisions are shown to add more heat into the system or inject mechanical assistance to further elevate the technology to provide a bigger output. The main advantage with the Stirling cycle system is that any heat source may be used to provide the thermal energy and hence may be suitable for use in a hybrid system. Liquid piston systems pump water directly which is then collected in a storage tank to irrigate fields using the drip irrigation method.

Two stroke piston systems have also been proposed that function like the Stirling cycle systems. Metal hydride systems have shown the best results in this providing the largest pumping head and flow of up to 2000 l using just a 1 m² flat plate collector. However, the use of metal hydrides makes this technology inaccessible to remote locations and farmers.

Based on the research undertaken solar thermal technologies utilising the Stirling engine holds the highest potential for small scale remote farms usage if the correct infrastructure is available for solar power concentration. Solar concentration technology that is cheap, effective and portable is required for this. Parabolic concentrators and dish concentrators provide compact solutions; however, they can be expensive to purchase. Local alternatives utilising local materials to build concentration systems may be proposed, which will reduce the cost as well as carbon footprint of the system. Utilising the technology to produce electricity is not viable, hence direct mechanical use for pumping is recommended in conjunction with a water storage tank is the optimal solution, this can be seen in Fig. 19.

A hybrid system may be proposed that combines the Stirling pump with and external mechanical system assist for the displacer in the case of inadequate solar irradiation like that proposed by Jokar and Tavakolpour-Saleh [72]; however, their use of solar panel and battery system defeats the investment cost aspect. Other external assistance solutions such as wind power may be investigated based on local resources availability.
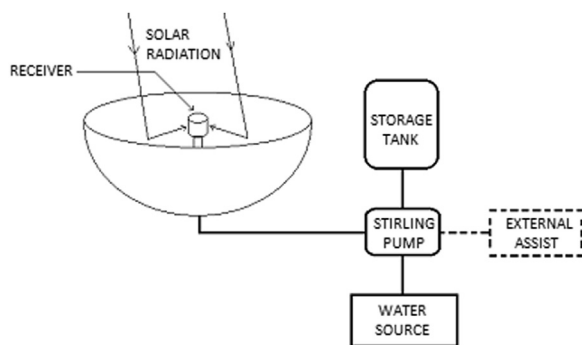

Fig. 19. Schematic of the most effective solar thermal water pumping system for remote rural areas based on literature reviews.

6. Future of solar powered water pumping systems

In terms of efficiency, solar thermal pumping systems conjure a maximum measured efficiency of 3% in comparison to 6% from photovoltaics. But the efficiency shouldn't be the main priority in the selection of the appropriate technology, especially since the source is renewable. The main factors hence are Cost and the impact on the environment.

A locally produced solar thermal system would be more cost effective and environmentally friendly in comparison to PV panels, as far as initial investments are concerned for remote area irrigation. The issue with regards to solar thermal powered technologies is that, the amount of research undertaken on these irrigation systems is very low; however, commercial technology exists that utilise thermal energy, but have not been studied critically.

The ease and accessibility of Stirling systems make it a viable option for testing and innovation, take for instance, SUNORBIT, a company from Germany, have produced a concentrated solar system capable of 500 W, 10 m head, 80,000 L/day known as the SUNPULSE [79]. See Fig. 20. The system uses a foldable dish concentrator with a heat storage powering a γ-type Stirling engine. The pump has been tested across Europe, Africa, Asia and Australia and is estimated to cost US\$ 2500.

Tested by TÜV labs, the system is shown to meet the World Bank target of water cost for rural areas of 6 cents/m³. As per tests, the system designed can provide 2.4 cents/m³.

Similar systems have been researched recently however, most of the research conducted focus on the potential of the Stirling cycle for the generation of electricity. These systems tend to be more expensive including dual axis solar tracking and large concentrators. Barreto and Canhoto [82] modelled a Stirling engine including a dish solar concentrator system, thermal receiver, and functioned as per three cycles, thermal cycle, mechanical (β-type Stirling engine) and electric energy conversion. The global efficiency of the system was recorded to be 10.4%. Combine that a 70% efficient pumping system, a pumping system efficiency of 7.28% available.

Based on the concentration factor, the efficiency was mapped as per shown in Fig. 21. There is a definite loss by converting mechanical energy to electrical energy in this system. Furthermore, a β-type Stirling engine is not the most efficient Stirling engine.

Using the basis of the study performed by Barreto and Canhoto [82], and understanding the SUNPULSE technology will help develop a model based on theoretical and real life results to help design systems that best matches the scenarios presented for remote rural irrigation and thus develop apposite solar thermal water pumping technology to match the performance of solar PV solutions, while keeping overall costs down and being more environmental friendly.

7. Conclusions

PV powered water pumping technologies are well developed, easily accessible and require almost no maintenance over the course of the lifetime of the technology. Studies suggest that the best way to optimise the cost and design of the PV powered system is to understand the requirements of the crop and perform extensive site survey to analyse the working conditions of the system. This is seen in relation to the use of a battery system where cost savings have been achieved in certain scenarios without using the battery while in other applications it was found that a battery in fact reduces costs. While the cost of PV system, over the course of its lifetime, is much lower in comparison to diesel powered systems, the initial investment cost is much higher and often too much to bare for small scale rural farmers. Furthermore, if the purpose of solar panels is to reduce the impact on the environment, it falls short due to a substantial carbon footprint because of the manufacturing and transportation impacts of the technology.

This study identifies that there is a huge potential for solar thermal
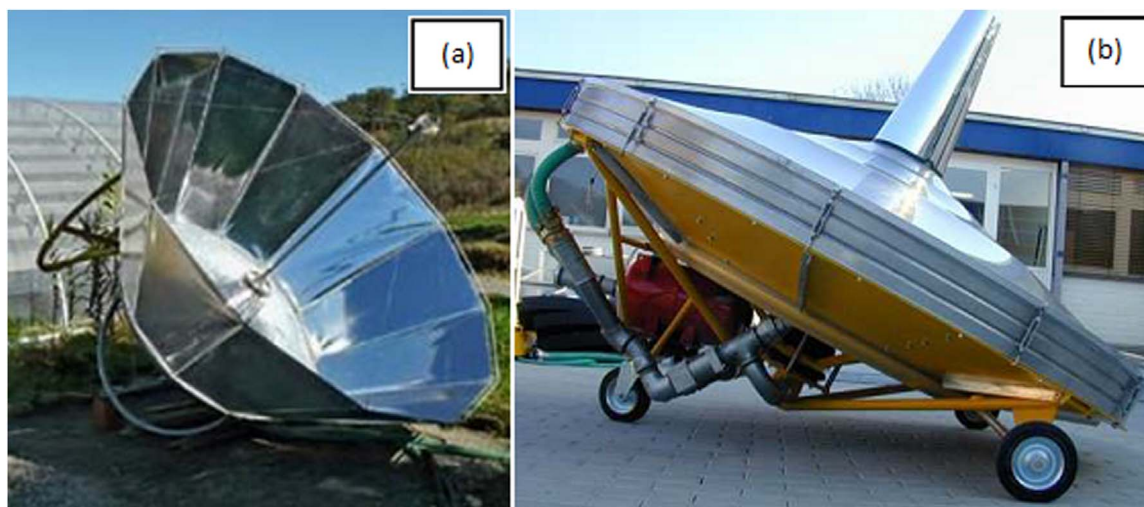
Fig. 20. (a) Solar Stirling water pump with dish [80] (b) SUNPULSE Stirling system [81].
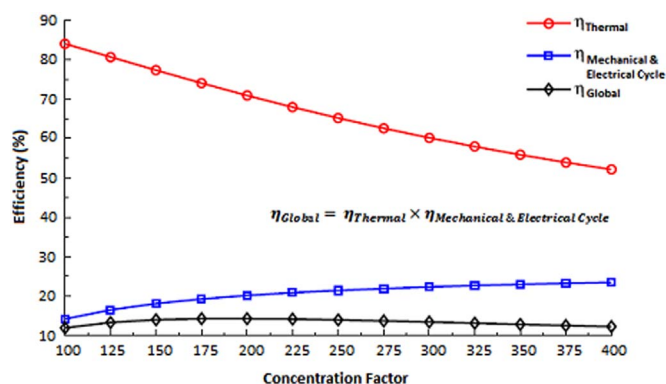

Fig. 21. Solar concentration factor and its effect on efficiency [82].

technology to meet the requirements of the small scale rural farmer by using a solar thermal water pumping system but the research on these systems are minimal, there is very few data available on the feasibility of these technologies especially for small scale purposes. Organic Rankine Cycle systems are the most common form of concentrated solar thermal power generation systems utilised for irrigation, however, these systems are feasible only on a large scale. That said, commercial technologies and studies in recent development in Stirling engines positively depict solar thermal water pumping capabilities keeping costs to a minimum and appreciably reducing the carbon footprint through the utilisation of local resources and local manufacture while matching the performance of PV technology.

Acknowledgement

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