Renewable and Sustainable Energy Reviews 49 (2015) 1084–1099

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies

S.S. Chandel [a,*], M. Nagaraju Naik [a], Rahul Chandel [b]

[a] Centre for Energy and Environment Engineering, National Institute of Technology, Hamirpur 177005, Himachal Pradesh, India
[b] Solar Photovoltaic Engineering Division,Welspun Energy Ltd., Noida 201307, Uttar Pradesh, India

ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form
12 March 2015
Accepted 23 April 2015

Keywords:
Solar water pumping
Solar energy
Photovoltaics
Performance analysis
PV degradation
Irrigation

ABSTRACT

The deficit in electricity and high diesel costs affects the pumping requirements of community water supplies and irrigation; so using solar energy for water pumping is a promising alternative to conventional electricity and diesel based pumping systems. Solar water pumping is based on photovoltaic (PV) technology that converts solar energy into electrical energy to run a DC or AC motor based water pump. The main objective of the study is to present a comprehensive literature review of solar pumping technology, evaluate the economic viability, identify research gaps and impediments in the widespread propagation of solar water pumping systems and technology. The study focuses on update on solar water pumping technology, performance analysis, optimum sizing, degradation of PV generator supplying power to pump, economic and environmental aspects and advances in PV materials and efficiency improvements. An update on the current state of research and utilization of solar water pumping technology is presented. Factors affecting performance of PV water pumping system, degradation of PV modules and efficiency improving techniques of PV water pumping systems are identified. Solar water pumping is found to be economically viable in comparison to electricity or diesel based systems for irrigation and water supplies in rural, urban and remote regions. The investment payback for some PV water pumping systems is found to be 4–6 years. The recent Indian incentives for PV pumping and policy initiatives for the promotion of solar water pumping in developing countries are also discussed. Potential follow-up research areas are also identified.

Contents

1. Introduction . . . 1085
2. Solar photovoltaic water pumping technology . . . 1085
   2.1. Current state of technology . . . 1085
   2.2. Principle of a solar water pump . . . 1086
   2.3. Types of solar water pumps . . . 1086
   2.4. Water supply source . . . 1086
   2.5. PV generator . . . 1086
   2.6. Motors for PV based pumps . . . 1087
   2.7. Solar pumps . . . 1088
      2.7.1. Dynamic pumps . . . 1088
      2.7.2. Displacement pumps . . . 1088
3. Literature survey of PV water pumping systems . . . 1088
   3.1. Performance parameters of a solar pump . . . 1088
   3.2. Overview of performance analysis research . . . 1089
   3.3. Optimal sizing of PV pumping system . . . 1090
   3.4. Performance improvement of PV water pumping systems . . . 1092
   3.5. Economic and environmental aspects . . . 1093

* Corresponding author. Tel.: +91 9418011957; fax: +91 1972 223834.
E-mail addresses: chandel_shyam@yahoo.com, sschandel2013@gmail.com (S.S. Chandel).

http://dx.doi.org/10.1016/j.rser.2015.04.083
1364-0321/

3.6. Impact of PV generator degradation on pumping system performance . . . 1094
4. Viability of PV pumping system technology. . . 1095
4.1. Initiatives in developing countries . . . 1095
4.2. Indian initiative on PV pumping. . . 1095
5. Material and efficiency advancement in photovoltaics . . . 1096
6. Results and discussion. . . 1097
7. Conclusions . . . 1097
References . . . 1098

1. Introduction

Water pumping worldwide is generally dependent on conventional electricity or diesel generated electricity. Solar water pumping minimizes the dependence on diesel, gas or coal based electricity. The use of diesel or propane based water pumping systems require not only expensive fuels, but also create noise and air pollution. The overall upfront cost, operation and maintenance cost, and replacement of a diesel pump are 2–4 times higher than a solar photovoltaic (PV) pump. Solar pumping systems are environment friendly and require low maintenance with no fuel cost [1]. Keeping in view the shortage of grid electricity in rural and remote areas in most parts of world, PV pumping is one of the most promising applications of solar energy. The technology is similar to any other conventional water pumping system except that the power source is solar energy. PV water pumping is gaining importance in recent years due to non-availability of electricity and increase in diesel prices. The flow rate of pumped water is dependent on incident solar radiation and size of PV array. A properly designed PV system results in significant long-term cost savings as compared to conventional pumping systems. In addition, tanks can be used for water storage in place of requirement of batteries for electricity storage [2].

Agricultural production in developing countries is largely dependent on rains and is adversely affected by the non-availability of water in summers. However, maximum solar radiation is available in summers as such more water can be pumped to meet increased water requirements. Urban water supply systems are also dependent on electricity to pump water in towns. There is a wide scope to utilize PV pumping systems for water supplies in rural, urban, community, industry and educational institutions.

In this study, a review of current state of research and utilization of solar water pumping technology is presented. The study focuses on recent advancement of the PV pump technology, performance evaluation, optimal sizing, modeling and simulation, degradation of PV generator supplying power to pump, economic and environmental aspects, and viability of PV water pumping systems for irrigation, livestock and community water supplies in rural, urban and remote regions. The research findings of solar photovoltaic water pumping systems of different configurations are presented for further follow-up research. The main objective of the study is to present current research status, and identify research gaps and impediments in the widespread propagation of solar water pumping technology. The strategy and policy issues for the promotion of PV water pumping are also presented.

The paper is organized as follows: current state of solar water pumping technology is described in Section 2; the literature survey of PV water pumping system studies and research findings are given in Section 3; in Section 4 the viability and initiatives taken are presented. Results and discussion are presented in Section 6. Conclusions are given in Section 7.

2. Solar photovoltaic water pumping technology

2.1. Current state of technology

A SPV water pumping system consists of a PV array, a DC/AC surface mounted/submersible/floating motor pump set, electronics. The PV Array is mounted on a suitable structure with a provision of manual or automatic tracking. Water is pumped during day and stored in tanks, for use during day time, night or under cloudy conditions. The water tank acts as storage and generally battery is not used for storage of PV electricity; however, for specific reliable requirements it can be used. The components

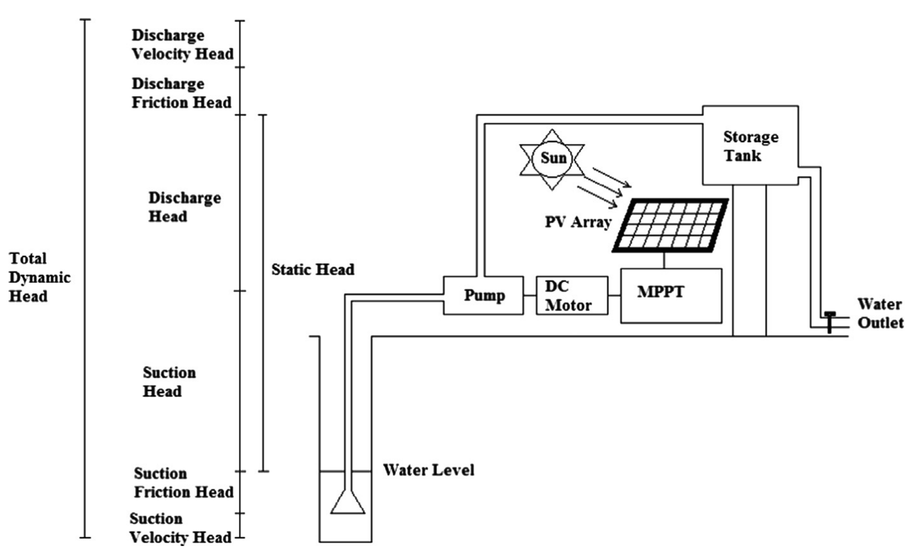

Fig. 1. Schematic of a direct coupled solar photovoltaic water pumping system with MPPT.

used in the PV water pumping system should conform to the national/international specifications, whichever is applicable in a country.

Direct coupled DC solar pumping was first introduced in the field in the late 1970s. Earlier PV water pumping systems have limitations of overall performance of the system due to lack of proper design. Since then, manufacturers have refined their products to improve the performance and reliability. The steady fall in prices of solar photovoltaic (PV) panels have resulted in making solar pumping economically viable for an increasingly wide range of applications. Direct coupled DC solar pumps are simple and reliable [3] but cannot operate at maximum power point of PV generator as the solar radiation varies during the day from morning till evening. However, adding a maximum power point tracker (MPPT) and controls/protections improve the performance of a PV pump.

PV water pumping systems have shown significant advancements in the last decade. The first generation PV pumping systems used centrifugal pumps usually driven by DC motors and variable frequency alternating current (AC) motors, with proven long-term reliability and hydraulic efficiency varying from 25% to 35%. The second generation PV pumping systems use positive displacement pumps, progressing cavity pumps or diaphragm pumps, generally characterized by low PV input power requirements, low capital cost and high hydraulic efficiencies of even 70% [4]. The current solar pumping technology uses electronic systems which have further increased the output power, performance of the system and overall efficiency of the system. The controller provides inputs for monitoring storage tank levels, controlling the pump speed and uses maximum power point tracking technology to optimize the water. Advancement has taken place in the tracking mechanism of PV arrays from manual tracking to dual axis automatic tracking systems by microcontroller programming. Tracking the sun reduces the physical size of PV panel area required for a given output, improves power yield, overall efficiency of the system and return on investment. Tracking of a solar pumping system extends the time for peak water yield. The solar pumps available in the market can lift water from 5 m to more than 200 m with outputs of up to 250 m^3/day.

For the past 15 years significant improvement has been done in helical motor pumps (positive displacement pumps) which are submersible and last for many years and are powered by similar motors as used for centrifugal pumps. Advancement has been in the field of controllers for large size PV arrays in the order of 25 kW with 100 kW controllers expected to be developed in near future [5]. PV module costs have significantly declined and are available at a rate of US$ 0.59/Wp in 2014 as compared to around US$ 1/Wp in 2012 in India [6]. This significantly affects the overall cost of the pumping system since PV modules represent 60–80% of the total cost of a PV system. The steady increase in cost of diesel and gasoline prices over the years and decrease in PV system costs make PV pumping attractive from financial perspective also. Furthermore, crystalline PV modules with high efficiencies of 16.84–21.5% are available in the International market in 2014 [7,8]. In the following section an overview of solar water pumping technology is presented.

2.2. Principle of a solar water pump

Solar water pumping is based on PV technology that converts sunlight into electricity to pump water. The PV panels are connected to a motor (DC or AC) which converts electrical energy supplied by the PV panel into mechanical energy which is converted to hydraulic energy by the pump. The capacity of a solar pumping system to pump water is a function of three main variables: pressure, flow, and power to the pump. For design purposes pressure can be regarded as the work done by a pump to lift a certain amount of water up to the storage tank. The elevation difference between the water source and storage tank determines the work, a pump has to do. The water pump will draw a certain power which a PV array needs to supply.

A schematic of a typical direct-coupled DC solar photovoltaic water pumping system with MPPT is shown in Fig. 1.

2.3. Types of solar water pumps

The various types of current configurations of direct coupled DC and AC solar water pumping systems being used worldwide are shown in Figs. 2–4.

2.4. Water supply source

Water supply source can be a pond, stream, spring, deep drilled well or a river. Water source must recharge faster than water pumping rate. In case pumping rate is faster than recharging rate of water source, the reservoir can dry which should be avoided to prevent damage to the pump. Main variables for system design are water reservoir volume, recharge rate and cost.

2.5. PV generator

PV generator of a solar pump consists of PV modules connected in series and parallel combination as per motor voltage requirement. A PV module consists of solar cells which convert solar

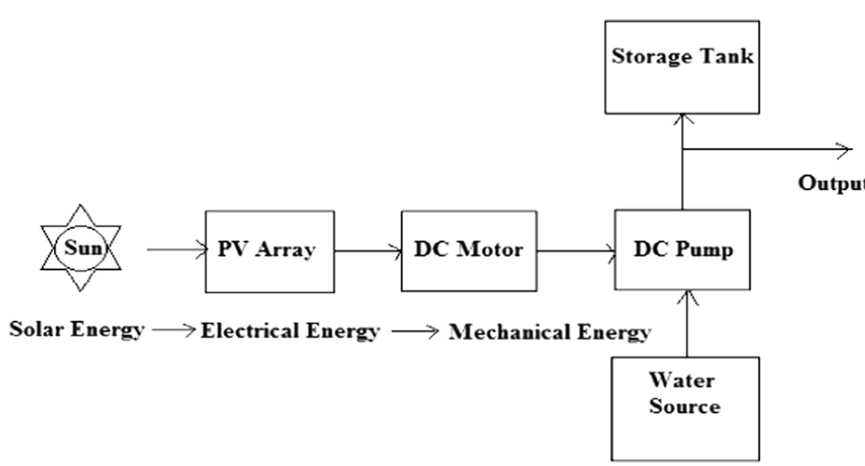

Fig. 2. Block diagram of a direct coupled PV DC water pumping system.

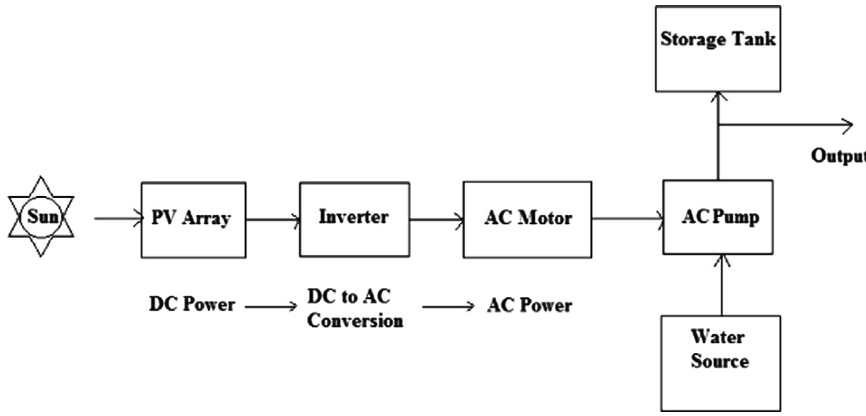

Fig. 3. Block diagram of a PV AC water pumping system.

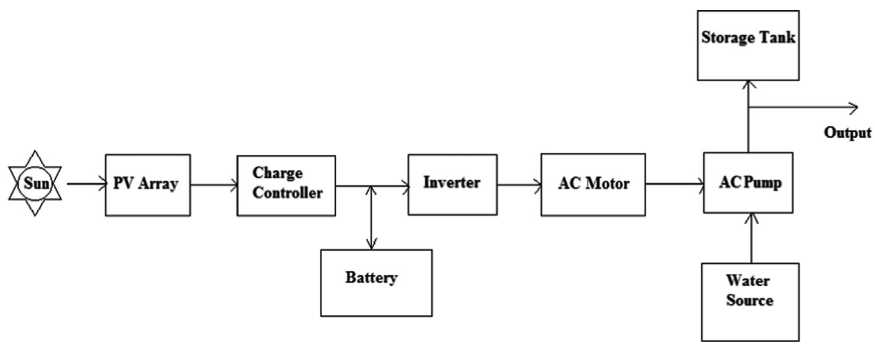

Fig. 4. Block diagram of a PV water pumping system with battery storage.

radiation into direct electricity. At a given illumination the current–voltage relation for a solar cell single diode model is given by

$$I = I_L - I_o\left\{\exp\left(\frac{q}{akT_c}(V+IR_s)\right)-1\right\}-\frac{V+IR_s}{R_{sh}} \quad (1)$$

where I_L is light generated current, I_o is the diode reverse saturation current, a is the ideality factor which varies from 1 to 5 and indicates solar cell characteristics deviation from ideal behavior, q is the charge on electron, k is the Boltzmann constant, T_c is the cell temperature, R_s is the series resistance and R_{sh} is the shunt resistance ; R_{sh} has large value and R_s is small so it can be neglected in the analysis.

The energy extracted from a PV module is dependent on climatic conditions. In fact, such module has an optimum operating point, called the maximum power point (MPP), which depends on the intensity of illumination. In order to extract maximum power from a PV module it is connected to DC–DC converter or DC–AC converter (inverter) controlled by maximum power point tracking (MPPT). A linear current booster is installed between PV panels and pump which turns on the pump during low light conditions. Linear current boosters need to be sized as per the pump voltage and panel output. A combiner box is used to make wiring safe if more than one panel is used. The circuit breakers are installed in the box for safe and quick shutoff of the panels in case servicing is required by the system. The circuit breakers can also be used as a switch for turning the pump on and off.

A pump will only require a certain power to produce a certain amount of pressure and flow. Therefore the PV array size has to be optimized for the required amount of power. A higher capacity PV generator will allow the pump to start earlier and operate for longer period during the day under low insolation conditions. However, adding more PV panels than actually required will add to the cost. The large panel surface area also acts as a linear current booster, as such a separate linear current booster may not be required.

2.6. Motors for PV based pumps

PV modules produce direct current so DC motors are most commonly used in a low power solar water pumping system. Solar pump systems below 5 kW generally use DC motors. These motors are of two types: DC motor with brushes and without brushes. DC motor with brushes requires frequent maintenance due to commutator and sliding brush contacts especially in submersible applications where the pump has to be removed frequently from the water well for replacing brushes. A permanent magnet synchronous (PMSM) brushless DC motor coupled to a centrifugal pump is found to be a better alternative than a DC motor for low power direct coupled PV water pumping systems. This type of motor is small in size and rugged as compared to an AC motor.

The cost and maintenance problems of DC motors have resulted in the use of induction motors (IM) which require an inverter to be used between PV array and the motor. PV pumping system based on induction motor is rugged, reliable and maintenance-free with increased efficiency and provides more possibilities for control strategies in comparison to DC motors [9]. Chandrasekaran and Thyagarajah [10] have carried out a detailed analysis of DC and AC motors used in PV pumping which shows that the efficiency and dynamic performance of PMDC motor is better than an AC single-phase induction motor.

Nabil et al. [11] studied the performance characteristics of a brushless asynchronous reluctance motor run by a PV generator under different insolation levels and proposed a control strategy to maintain the motor voltage within a permissible range and PV array to operate as close to the maximum power point (MPP). The authors have found that using this type of motor leads to improvement in the performance of PV pumping system.

2.7. Solar pumps

Solar water pumps are rated as per voltage supplied and require accessories like filters, float valves, switches, etc to function optimally. Solar pumps are constructed from high quality low lead marine grade bronze and stainless steel and are designed for corrosion-free and maintenance-free service even in harsh environment with long term performance and reliability.

Solar pumps are classified into three types according to their applications: submersible, surface, and floating water pumps.

A submersible pump draws water from deep wells, and a surface pump draws water from shallow wells, springs, ponds, rivers or tanks, and a floating water pump draws water from reservoirs with adjusting height ability. The motor and pump are built in together in submersible and floating systems. In the surface system, pump and motor can be selected separately to study the performance of system along with controller and PV panel. A pump produces a unique combination of flow and pressure i.e. high-flow/low-head to low-flow/high-head for a given power input.

Broadly, pumps can be classified under two categories based on operating principle: dynamic pumps and positive displacement pumps. Dynamic pumps operate by developing a high liquid velocity and pressure in a diffusing flow passage. The efficiency of dynamic pumps is lower as compared to positive displacement pumps but have comparatively lower maintenance requirements. Positive-displacement pumps operate by forcing a fixed volume of fluid from the inlet pressure section of the pump into the discharge zone of the pump. These pumps generally tend to be larger than equal-capacity dynamic pumps. Centrifugal pumps and axial flow pumps are dynamic pumps.

2.7.1. Dynamic pumps

In centrifugal pumps, water is sucked by the centrifugal force created by impeller and the casing directs the water to the outlet as the impeller rotates. Water leaves with a higher velocity and pressure than it had when it entered. Centrifugal pumps directly interfaced with the solar panels are used for low-head applications. A centrifugal pump has the ability to match with the output of solar generator. The operation of such pumps takes place for longer periods even at low insolation levels, and load characteristic is in close proximity to PV maximum power point (MPP). Centrifugal pumps have relatively high efficiency, but decreases at lower speeds, which can be a problem for a pumping system at low insolation. Centrifugal pumps are economical from shallow to medium lifts (up to 80 m) with large flow rates. Axial Flow Pumps are dynamic pumps that use the propeller to create a lift action of the fluid in the pipe. These pumps are often used in wet-pit drainage, low-pressure irrigation, and storm-water applications.

2.7.2. Displacement pumps

Screw pump and Piston pump are positive displacement pumps. A displacement pump also called volumetric pump, has different speed–torque characteristics and are not well suited to be connected directly to PV panels. When such pumps are used a power conditioning unit and maximum power point tracking system has to be incorporated between the solar panel and pump. These pumps are of the rotating impeller type, which throws the water radially against a casing shaped in such a way that the momentum of water is converted into useful pressure for lifting. In displacement pumps, the water output is directly proportional to the speed of pump, but almost independent of head. In a screw pump, a screw traps water in suction side of the pump casing and forces it to the outlet. In a piston (diaphragm) pump the motion of piston draws water into a chamber using the inlet valve, and expels it to the outlet using the outlet valve. Piston pumps are much more complex with a lot of moving parts and require oil lubrication inside the pump which might be a potential risk in water well. Typically these are used in low voltage (24–48 V) applications with small daily flows (up to 5 m^3/day) for lifts up to150 m (max. 2 m^3/day).

The selection of a pump for solar water pumping is dependent on water requirement, height to lift water and water quality. An optimum solar pump is to be selected which can meet the daily water flow and pumping head requirements.

3. Literature survey of PV water pumping systems

Photovoltaic (PV) power for irrigation is cost-competitive in comparison to traditional energy sources for small-scale water pumping requirements. With the continuous increase in fossil fuel cost and reduction in peak watt cost of solar cells due to mass production, the photovoltaic power is to become further economical in future [12]. PV powered water pumping systems have become attractive for livestock and agriculture applications in remote locations with limited access to conventional electricity [13]. A number of studies have been carried out on performance evaluation, optimization, sizing techniques, efficiency improvement, and factors affecting system performance, economical and environmental aspects of PV pumping systems. The highlights of the research investigations are presented in this section.

3.1. Performance parameters of a solar pump

The performance of PV water pump mainly depends on the water flow rate which is influenced by weather conditions at the location, especially solar irradiance and air temperature variations. The performance of solar pump depends on the water requirement, size of water storage tank, head (m) by which water has to be lifted, water to be pumped (m^3), PV array virtual energy (kWh), Energy at pump (kWh), unused PV energy (kWh), pump efficiency (%), and system efficiency (%) and diurnal variation in pump pressure due to change in irradiance and pressure compensation [1]. The efficiency of PV technology used in PV generator has also a great influence on the performance. Besides the degradation of PV panels is one of the important parameters which affect the performance of a solar pump.

The performance of solar water pumping system depends on the following parameters:

- Solar radiation availability at the location;
- Total Dynamic Head (TDH): Sum of suction head (height from suction point till pump), discharge head (height from pump to storage inlet) and frictional losses;
- Flow rate of water;
- Total quantity of water requirement; and
- Hydraulic energy: potential energy required in raising the water to discharge level.

Hydraulic energy E_h (kWh/d) required per day to supply a volume V of water (m^3) at TDH is given by [1]:

$$E_h = \rho \times g \times V \times TDH \tag{2}$$

where ρ is the water density, g is the acceleration due to gravity (9.81 m/s^2), TDH is the total dynamic head (m) is sum of static head (m) and friction losses (m).

Solar photovoltaic array power P_{pv} required is given by

$$P_{pv} = E_w/(I_T \times \eta_{mp} \times F) \tag{3}$$

where I_t is the average daily solar irradiation (kWh/m^{2}day) incident on the plane of array, F is the array mismatch factor, η_{mp} is the daily subsystem efficiency.

The amount of water pumped V (m^3) is given by

$$V = (P_{pv} \times I_T \times \eta_{mp} \times F)/(\rho \times g \times TDH) \tag{4}$$

The efficiency of the motor-pump system η_{mp} is given as follows:

$$\text{Efficiency} = \text{hydraulic energy output/input energy input} \tag{5}$$

Efficiency of PV array (%) is given by

$$\eta_{pv} = \frac{P_{pv}(W)}{I_T(W/m^2) \times A_c(m^2)} \times 100 \tag{6}$$

The overall solar water pump system efficiency is obtained as

$$\eta_{total} = (\eta_{pv} \times \eta_{mp}). \tag{7}$$

3.2. Overview of performance analysis research

In this section performance evaluation methodologies used in various studies are reviewed to provide further insight to the researcher.

Gad [14] developed a methodology for performance prediction of a direct coupled PV water pumping system in South Sinai, Egypt using a computer simulation program. The program simulates the hourly performance of the system at any day of the year, under different PV array orientations. The system is found to be capable of pumping 24.06 l/day, 21.47 l/day and 12.12 l/day in summer solstice, equinoxes and winter clear sky days respectively. The calculated PV array efficiency ranges from 13.86% in winters to 13.91% in summers.

Katan et al. [15] analyzed the performance of a solar water pumping system consisting of a PV array, sun-tracker, a permanent-magnet (PM) DC motor, a helical rotor pump and found that the performance of the system is enhanced when maximum power point tracker (MPPT) and a sun-tracker are added to the system. The analysis of the PV array was carried out using PSPICE software. Theoretical results are verified by field tests.

Loxsom and Veroj [16] developed and tested an algorithm to estimate the long term monthly performance of a solar photovoltaic water pumping system without any battery storage system for four locations in USA by using average monthly solar insolation input data and estimated the total monthly volume of water pumped with hourly simulation. Khan et al. [17] designed a solar photovoltaic water pump by adding a DC–DC buck converter to provide current boosting to the DC pump. No battery and inverter are used in the system so as to reduce the cost and maintenance. The highest no load speed goes up to 3000–3200 revolutions per minute (rpm). The results from the no load test revealed that the integration of DC motor with the centrifugal pump has matched quite perfectly. A direct coupled system without a Power Conditioning Unit (PCU) is compared with DC–DC convertor type system. The DC motor operating voltage, operating current, shaft rpm and the discharge rate at different pressures during different times of a day for both systems are measured and improvement in the electrical power output is found in the designed DC water pumping system.

Mokeddem et al. [18] investigated the performance of a directly coupled DC powered PV water pumping system. The system operates without battery and electronic controls. The motor-pump efficiency did not exceed 30%, which is typical for a directly-coupled photovoltaic pumping system; yet such a system is suitable for low head irrigation in remote areas. The efficiency of the system can be increased by selecting the size of PV array, its orientation and motor-pump system.

Kou et al. [19] developed a method to predict the long-term performance of a direct-coupled PV pumping system. The method uses PV module and pump–motor manufacturer data in the study. Weather data are generated from monthly averages of horizontal radiation and ambient temperature. The method predicts monthly pumped water to within 6% of TRNSYS prediction based on hourly weather data and can be used in designing and estimating the long-term performance of a PV water pumping system for US climates. Hadj et al. [20] analyzed the performance of different PV water pumping systems for 4 different locations: Algiers, Bechar, Oran and Tamanrasset in Algeria using typical meteorological year (TMY) data. The study is carried out for 3 different profiles: three tank capacities; two PV modules types; two PV array configurations and several pumping heads applied to two centrifugal pumps and concluded that PV generator costs can decrease if the simulation program accounts for the type of pump, pumping head and daily load profile. The system can be optimized by studying individual requirements using computer program based on mathematical models of a motor pump, PV generator.

Pande et al. [21] designed and developed a PV pump operated drip irrigation system for arid regions considering different design parameters like pump size, water requirement, diurnal variation in pump pressure due to change in irradiance and pressure compensation in the drippers. Authors reported that a PV system with (900 Wp PV array, 800 W DC motor-pump mono-block) can provide 70–100 kPa pressure at the delivery side with a discharge of 3.4–3.8 l/h from each dripper during different hours of the day. The emission uniformity was found to be 92–96% in a field of 1 ha. It is suggested that PV water pumping systems need to be extensively tested for water harvesting tanks with lower suction head for growing orchards in arid region.

Mohanlal et al. [22] studied and analyzed the performance of a PV-powered DC (PM) motor coupled with a centrifugal pump at different solar intensities and corresponding cell temperatures. The experimental results obtained are compared with calculated values, and found that this system has a good match between the PV array and the electro-mechanical system characteristics. The authors reported that through manual tracking i.e., changing the orientation of PV array, three times a day to face Sun, the output obtained is 20% more as compared to the fixed tilted PV array.

Alghuwainem et al. [23] investigated the steady-state performance of a PV powered DC motor driving an isolated three-phase self-excited induction generator (SEIG) and found that SEIG is a perfect load match for a PV powered DC motor with the PV generator for maximum utilization of efficiency. The use of a SEIG avoids the need for matching devices or peak power trackers which increases the total system cost. It is found that due to the unique torque speed characteristics of the SEIG, the utilization efficiency is close to maximum at all insolation levels with no peak-power tracking. The proposed arrangement is useful as part of an integrated renewable energy system.

Benghanem et al. [24] determined an optimum PV array configuration, which supplies optimum energy to a DC helical pump, under the outdoor conditions at Madinah in Saudi Arabia. Four different PV array configurations are tested (6 series × 3parallel), 24 modules (6 series × 4 parallel), 24 modules(8 series × 3 parallel) and 24 modules (12 series × 2 parallel). The comparative performance of four PV water pumping system configurations (PVWPS1, PVWPS2, PVWPS3 and PVWPS4) shows that the configuration PVWPS3 is suitable to supply the maximum daily 22 m^3/day quantity of water needed. The system efficiency comparison shows that the (PVWPS3) is more appropriate for this location. However for optimal energy exploitation, an efficient use of the PV pumping system design is required for this site

Atlam and Kolhe [25] analyzed the operation of directly PV powered DC PM (direct current permanent magnet) motor propeller system for the selection of motor parameters and found that the performance of the system mainly depends on the incident solar radiation, operating cell temperature, DC motor and propeller load parameters. It is observed that the operating points of the PV DC PM motor propeller system matches very closely with the maximum power points (MPPs) of the PV array. Authors concluded that the system performance and efficiency can be improved by matching the output torque speed characteristics of this system with the electromagnetic torque speed characteristics of motor under different solar radiation levels.

Setiawan et al. [26] presented various stages of development of a solar water pumping system to solve water supply problem in Purwodadi Village, Gunungkidul, India. The authors suggested two important design parameters which are: analysis of piping system to determine the type of pump to be used and the power system planning. PV water pumping system developed was able to lift water to 1400 m. The system uses 32 solar PV panels to produce 3200 Wp maximum power and operates 2 submersible pumps. The flow rate of water produced is about 0.4–0.9 l/s.

Reddy and Reddy [27] presented control system of electrical power supplied by PV to a single phase induction motor which is used for water pumping applications. The overall performance of a photovoltaic system can be improved with dynamic models for the Z-source inverter, single phase induction motor and neural network based maximum power point tracking. Bhave [28] highlighted the potential of solar PV water pumping systems in India and concluded that there is a vast scope of replacing traditional and diesel pumps with solar pumps for low and medium head pumping applications but the capital costs are very high. Solar water pumping systems are found to be more suitable for drinking water and minor irrigation requirements due to their cost, size factors considerations.

Eyad and Al-Soud [29] studied the potential of solar water pumping in Jordan and selected 10 sites based on the availability of solar radiation data under three categories: adequate, promising and poor and suggested other water pumping alternatives for these sites. Alawaji et al. [30] discussed components, basic operation and performance of water pumping and desalination in the remote areas of Saudi Arabia. The study reported that utilization of PV energy for water pumping and desalination is reliable and cost effective.

Kaka and Gregoire [31] studied the performance of a PV water pumping system in a village at 30 km of Keita (Niger) to meet the water needs of 500 persons and reported that the cost of one cubic meter of water pumped by the PV system is more advantageous than other systems. PV water pumping is found to be well suited for arid and semi-arid areas due to the existence of underground water potential, and large solar energy potential of more than 6 kWh/m².

Padmavathi and Daniel [32] analyzed various photovoltaic water pumping options and domestic water requirements for Bangalore city in India and concluded that PV panels ranging from 60 Wp to 500 Wp are sufficient for residential buildings in Bangalore and suggested that government policies and regulations are required for the promotion of using PV water pumps in urban domestic sector.

Badari et al. [33] studied feasibility of a PV pumping system under real weather conditions using MATLAB Simulink by modeling each component of the system. The designed Simulink module can be used as a template to design solar DC powered water pumping system of required capacity. This simulation will be useful for solar pump manufacturers for optimizing the design of solar pump controller.

Ould-Amrouche et al. [34] developed a model using experimental results obtained with several motor-pump subsystems of different types and technologies. The results are compared by considering centrifugal and positive displacement motor-pump subsystems. The experimental tests are used to validate the developed model. Based on the motor-pump subsystem model, a method is proposed to estimate the amount of carbon dioxide (CO_2) emissions saved by using a PV water pump in comparison to diesel generators.

Maurya et al. [35] developed relationships between array power and borehole depth per capita water use, rainfall, borehole depth and capital cost of solar photovoltaic water pumping systems in Nigeria which would lead to increased performance, reliability, cost-effectiveness and adoption of the technology. Biji [36] proposed modeling of maximum power point trackers (MPPTs) with control system for PV water pumping systems by selecting the converter-chopping ratio of MPPT using artificial neural network (ANN). The models integrated by a MATLAB simulation program show increased power output by the system.

Jafar [37] presented a simple method for modeling the output of a solar photovoltaic water pumping system, which relies on easily measurable data. The procedure is applied to a Solar Star 1000 pumping system to develop a model that predicts the volume flow rate for a given head and irradiance. The model predicts the flow rates within 8% of the measured values. The small deviation is attributed to fluctuations in the solar irradiance and unsteady module temperatures during the measurements.

Flores et al. [38] developed a software tool that simulates PV pumping systems with sun tracker and the effect of the level of dirt on the PV generator surface. This effect is important for dry climates. The simulation tool is validated with the experimental data. The results of the simulation tool have been validated with experimental data from pumps installed at the test facility of Solar Energy Institute, Madrid, Spain.

Velvizhi and Subramanian [39] presented design aspects and simulation procedure leading to performance enhancement of PV based water pumping system. Authors presented two algorithms: two inductor boost converter and maximum power point tracking algorithm. The concept of maximum power point tracking is implemented using perturb and observe algorithm in MATLAB environment using Simulink blocks. A 400 W PV panel, two-inductor boost converter (TIBC) with auxiliary transformer, three phase inverter is implemented using Simulink blocks. Efficiency of water pumping is found to increase with MPPT as compared to a system without MPPT.

The highlights and research findings of performance evaluation studies of PV based water pumps in different countries are summarized in Table 1.

3.3. Optimal sizing of PV pumping system

The sizing of stand-alone photovoltaic systems is based on meeting electrical loads with lowest average daily solar insolation on the array surface usually during winter months.

Wagdy et al. [40] proposed a 'switched-mode' PV-powered pumping system. This system couples the pump to the PV array directly when the storage battery is fully charged, with the objective of maximum utilization of available solar radiation to minimize the cost by considering three basic parameters: PV array size, storage battery size and water tank size. Authors reported that the optimum solution is one that minimizes the PV array size because the array cost is the major item and found that increasing battery storage without increasing array size has little effect on system performance.

Table 1
Summary of PV water pumping system performance evaluation studies.

S. no.	Reference	Country	Application	Research findings
1	Gad [14]	Egypt	Domestic	Computer simulation program is used to simulate the performance of a proposed PV water pumping system.
2	Katan et al. [15]	Australia	Domestic	System efficiency increases with MPPT and sun tracker.
3	Loxsom and Veroj [16]	Thailand	Irrigation	Algorithm is developed to estimate the water pumped as per insolation.
4	Khan et al. [17]	Bangladesh	Rural water supply	System efficiency is increased by adding DC–DC buck converter for a direct coupled PV water pumping system.
5	Mokeddem et al. [18]	Algeria	Irrigation	System efficiency increased by orientation and sizing of PV array and motor pump system.
6	Kou et al. [19]	USA	Domestic	Predicted monthly water pumped by a system within 6% of TRNSYS prediction based on hourly data.
7	Hadj Arab et al. [20]	Spain	Domestic	Optimized a proposed PV water pumping system by studying individual requirements with a simulation program.
8	Pande et al. [21]	India	Irrigation	Reported 6 years pay-back period including subsidies on PV modules.
9	Mohanlal et al. [22]	Egypt	Irrigation	System efficiency is increased up to 20% by manually tracking thrice in a day.
10	Alghuwainem et al. [23]	Saudi Arabia	Irrigation	Self excited induction generator utilization avoids need for matching devices and tracking systems.
11	Benghanem et al. [24]	Saudi Arabia	Irrigation	Electronic array configuration should be included in order to match maximum power points of PV array with pump
12	Atlam and Kolhe [25]	Turkey	Domestic	System performance and efficiency can be improved by matching the output characteristics.
13	Setiawan et al. [26]	India	Irrigation	Two important design aspects for PV water pumping system are identified; analyzing piping system to determine the type of pump to be used and power system planning.
14	Reddy and Reddy[27]	India	Domestic	Configuration of the photovoltaic system can be improved with dynamic models for inverter, single phase induction motor and neural network based maximum power point tracking.

Argaw [41] presented a simple non-linear optimization technique which is used to solve the load matching problem of a PV water pumping system and reported that an optimum matching factor of best 0.74 and least 0.55 can be achieved using a 1.76 kWp M55 type PV array and M40USP5A-7 type motor/pump with SA1 500 DC/AC inverter interfacing device and suggested that it is possible to achieve a higher load matching factor by selecting carefully the proper size of array and motor pump.

Yahia et al. [42] developed an optimal sizing model to optimize the capacity sizes of different components of a standalone photovoltaic water pumping system using a water tank and analyzed a pumping system, which is designed to supply water for drinking and irrigation located in Ghardaia, Algeria. Authors simulated the PV water pumping system by using a developed program and determined the relationships between system power reliability and system configurations. The optimal configurations of the pumping system are determined for different desired system reliability requirements (LPSP) and the life cycle cost (LCC).

Kaldellis et al. [43] investigated a PV powered water pumping system which is able to meet additional electricity loads besides water pumping requirements at Athens, Greece. The results obtained by optimum sizing methodology are validated by experimental measurements. The two-level analysis is used for sizing of the system. The analytical approach is based on both the fundamental equations and the use of a numerical algorithm **PHOTOV-IV**. It is shown analytically and experimentally that a proper designed PV-based electricity generator with an appropriate energy storage device can meet the electricity needs of remote consumer along with water pumping.

Zvonimir and Margeta [44] simulated a PV irrigation water pumping system using a mathematical hybrid simulation optimization model for optimal sizing which uses dynamic programming for optimizing. The constraints are defined by the simulation model, by considering elements relevant to PV pumping system: bore holes, local climate, soil, crops, and irrigation system. The model was tested on two locations in Croatia. This model takes into consideration all characteristic values and their relations in the integrated system. It is found that the electrical power of PV generator, obtained by the new optimization method, is relatively smaller than that obtained by the usual method.

Hamidat and Benyoucef [45] proposed two mathematical models for PV pumping sizing. These models link the operating electrical power to the water flow rate of the pump versus total head. Two pumping subsystems of different technologies and manufacturers are studied. The first pump is the centrifugal pump which consists of a three-phase AC engine and a centrifugal pump. The second is the positive displacement pump which consists of a DC engine and a positive displacement pump. The results show that the displacement pump has better performance (higher efficiency, higher average volume of water pumped, and low energy losses) in comparison to a centrifugal pump. Firatoglu and Yesilata [46] used a simplified multi-step optimization procedure to improve utilization of a direct-coupled photovoltaic water pumping systems. The main highlights of the study are as follows:

- Calculated the optimal monthly slope by the linear search method,
- Determined optimal solar radiation interval by utilizability method,
- Selected optimal PV array configuration as determined by a non-linear search method based on statistical parameters. Algorithm developed is simple, fast, and has no numerical problems.

The performance of the system is predicted for 16 years between 1985 and 2001. The system performance is found good with a lower photovoltaic array area. The developed methodology is applicable to any other site in the world if long-term weather data are available.

Cuadros et al. [47] described a sizing procedure for a PV water pumping system for drip irrigation of an olive orchard in Spain which consists of the following stages:

- Determination of the irrigation requirements of the orchard as per characteristics of its soil-type and climate.

Table 2
Summary highlights of optimal sizing of PV water pumping systems.

S. no.	Reference	System type	Optimal sizing technique	Research findings
1	Wagdy et al. [40]	Direct coupled and battery buffered	Switched mode	Optimization provides maximum utilization of available solar radiation to minimize cost.
2	Argaw [41]	Direct coupled interfaced with PWM DC/AC inverter	Non-linear optimization	Optimum matching factor of 0.74 and 0.55 are found using DC/AC inverter interfacing device.
3	Yahia et al. [42]	Direct coupled	Loss of power supply probability (LPSP)	Program developed for relationship between system power reliability and system configurations.
4	Kaldellis et al. [43]	Battery based	Two-level analysis	Energy storage capability of a properly designed PV system determined analytically and experimentally to meet the electricity and water needs.
5	Zvonimir et al. [44]	Inverter coupled with AC pump	Hybrid simulation	Electrical power of the PV generator, obtained by the new optimization method is relatively smaller as compared to usual method.
6	Hamidat and Benyoucef [45]	Inverter coupled with AC pump	Conventional method	DC engine and a positive displacement pump shows best performance when compared with AC engine centrifugal pump.
7	Firatoglu and Yesilata [46]	Direct coupled	Multi-step optimization	System performance is found better for lower photovoltaic array area.
8	Cuadros et al. [47]	Inverter coupled with AC pump	Multi-step optimization	Output yield of crops can be improved by photo irrigation.

- Hydraulic analysis of the pumping system as per depth of aquifer and height needed to stabilize pressure in the water distribution network.
- Determination of peak photovoltaic power required to irrigate a 10 ha area considering overall yield of the photovoltaic–pump-irrigation system.

Optimal irrigation requirements for April–October months were determined. A 6 kWp PV pumping system is determined to supply the irrigation requirements for a 10 ha orchard flow rate of 161 m^3 per day. The summary of some optimal sizing research studies is presented in Table 2.

3.4. Performance improvement of PV water pumping systems

Odeh et al. [48] developed and validated a simulated model against laboratory and field data, using TRNSYS, for an AC PV water pumping system, utilizing real field data obtained from a system installed in Jordan. Authors studied the mismatch of pump characteristics, well system characteristics and average performance ratios for system, effect of insolation frequency and the PV array size, which affect PV system performance.

Ziyad and Dagher [49] presented a technique to improve the performance of a photovoltaic water pumping system by coupling a PV powered permanent magnet DC motor between PV array and screw-type volumetric water pump. In this method authors used a solid state Electrical Array Reconfiguration Controller (EARC), which senses the radiation as low, medium or high. Accordingly, controller chooses one desired set of *I–V* characteristics for starting and another desired set of *I–V* characteristics for steady state operation. Authors report that, using this technique considerably improves the pump's performance, particularly in the early morning, late evening and cloudy days thus providing a wide range of irradiance level for operation and extra pumping hour.

Abdolzadeh et al. [50] investigated the effects of spraying water over the photovoltaic modules of PV water pumping system performance under different operating conditions. The performance of a PV water pumping systems with two and three photovoltaic modules of 225 W each is studied by spraying water in parallel. It is found that due to a high module temperature, the module performance decreases and system performance also decreases. Spraying water on the PV modules decreases the module temperature and increases the module performance; in turn the pump flow rate increases considerably when the modules are cooled.

Azadeh [51] studied how increase in solar cell temperature of PV array and system head affect the performance of a PV pumping system installed in Kerman city, Iran. Authors provided water by a pump for cooling PV modules by covering the array surface with a thin film of water. Results reported that decrease in array nominal power and increase in system head increased the power generated by the array. Using this method results in reducing system costs as it can provide required power with lower array nominal power.

Abdolzadeh and Ameri [52] investigated the possibility of improving the performance of a photovoltaic water pumping system, by spraying water over the PV modules. The results show that spraying of water can achieve 12.5% mean PV efficiency. The mean flow rate at 16 m head on the test day was about 479 l/h in case of a system without water spray over PV modules whereas it reached 644 l/h for the system sprayed with water. Spraying of water on the photovoltaic modules leads to cooling of modules therefore improves the system and subsystem efficiencies.

Joao and Luis [53] proposed a new converter for PV water pumping systems without storage batteries. They designed a converter which drives a three-phase induction motor. The results show a peak efficiency of 91% at the rated power of 210 W for the DC/DC converter with three-phase voltage source inverter (VSI) and a peak efficiency of 93.64% for the dc/dc converter and suggested that the proposed solution is a viable option for more reliability.

Kim et al. [54] presented a regulated charge pump with an integrated optimum power point tracking (OPPT) algorithm for indoor solar energy harvesting. The solar cell voltage is regulated at the optimum power point while the pump output is regulated as per target voltage by OPPT and in and out regulation circuits. The proposed OPPT circuit and charge pump consume only 450 NW of quiescent power. The OPPT-on-demand scheme turns on the OPPT circuit only when it is necessary, which decreases the power consumption of the controller by 53% (from 850 NW to 450 NW). The circuit is also suitable for indoor solar energy harvesting under dim lighting conditions.

Eduard [55] proposed a PV water pumping system using a six-step square-wave inverter, both as a variable-frequency source and as peak-power tracker, which is coupled with a centrifugal water pump, and the controller is used to sense the changing conditions. Authors suggest that the system can be implemented by a simple microcontroller which requires control variables such as power, voltage, and current output of PV array to be fed back to the microcontroller. The insolation level is simulated by changing the coefficients of the voltage and current at different times. The data for the basic *V–I* characteristics are stored in one file, the light-

Table 3
Techniques used for improving efficiency of PV water pumping systems.

S. no.	Reference	Motor-pump set type	Type of technique used	Research findings
1	Odeh et al. [48]	AC	TRNSYS modeling	Increasing PV array size improves water output volume and subsystem efficiency and decreases PV efficiency.
2	Ziyad and Dagher [49]	DC	Electrical Array Reconfiguration Controller (EARC)	System improves pump's performance during cloudy conditions and provides extra pumping hours.
3	Abdolzadeh et al. [50]	DC	Spraying water on PV modules	Spraying water on the PV modules decreases modules temperature and increases modules' performance and pump flow rate…
4	Azadeh [51]	DC	Covering the surface of PV array by a thin film of water	Reduces system costs and provides needed power with lower array nominal power.
5	Abdolzadeh and Ameri [52]	DC	Spraying water over PV modules	Spraying water over the PV modules strongly improves the system and subsystem efficiencies.
6	Joao and Luis [53]	AC	Two-inductor boost converter (TIBC) and voltage source inverter (VSI)	Proposed solution is a viable option for more reliability.
7	Kim et al. [54]	DC	Optimum power point tracking (OPPT) algorithm	System designed is suitable for indoor solar energy harvesting under dim lighting conditions.
8	Eduard [55]	DC	Six-step square-wave inverter	System can be implemented by a simple micro controller.

intensity characteristics are stored in another file, and controller parameters, size of the steps, can be changed to observe different responses. Various techniques used for improving efficiency of PV water pumping systems are summarized in Table 3.

3.5. Economic and environmental aspects

With the non-availability/shortage of conventional electricity, cost escalation of diesel every year and that of PV modules steadily decreasing, PV pumping systems are becoming financially attractive as compared to electricity/diesel powered pumping systems in present times. The economic viability of PV systems has been assessed by a number of authors in recent past [55–59].

Odeh et al. [60] compared the economic viability of photovoltaic and diesel water pumping systems for different system sizes in the range 2.8–15 kWp, based on real data and three-year operational experience of eight installations. The possibility of reducing water unit cost by estimating demand pattern, storage tank sizing and selection of wells with low pumping head is discussed. The study shows that mismatch between water demand and supply pattern has a major effect on economic viability of the PV pumping systems and thus required to be examined seriously.

Jamil et al. [61] proposed a $20,000 solar water pumping system to meet the water requirements of an academic institution in New Delhi, India. The techno-economic analysis of PV based water pumping system is carried out and compared with an existing system. The payback period of the proposed system is found to be 4 years with estimated life of 20 years which can supply water at free of cost for 16 years which is a huge saving and also reduce the grid dependency of the existing electricity based pumping systems and diesel water pumping systems.

Hamidat [62] carried out an electrical and hydraulic performance analysis of a surface centrifugal pump for three PV arrays and several total dynamic heads at Algeria and concluded that the average yearly flow rate is about 60 m^3/ day for 14.5 m/head, the cost of water delivered is found to be US $0.04/$m^3$. The study recommends using surface PV pumps to supply water in the remote Sahara regions for the socio-economic development of the region.

Kaldellis et al. [63] carried out detailed measurements of an experimental PV water pumping system with a 610Wp PV generator which provides water daily to more than 200 consumers in remote locations of Greece and reported that the system operates reliably with relatively low electrical losses $\sim$10%, and is an environment friendly application.

Purohit and Kandpal [64] presented financial performance evaluation of a PV water pump in India, by estimating the present value, internal rate of return investment and unit cost of water including effects of financial incentives such as capital subsidy, accelerated depreciation-related income tax benefits and provision of a low interest loan on the break-even prices of diesel and electricity have been studied and reported that, with the higher costs PV pumps may not be financially viable to potential users in India.

Foster and Hanley [65] studied more than 130 types of PV water pumping systems of about 2 kWp size installed in eight states in Mexico. The increased viability of installations led to low prices, high quality and gaining foot hold in Mexico. Kumar and Kandpal [66] developed a method for quantification of CO_2 emissions and estimation of PV pump cost mitigation in India. The study shows that for a 1.8 kWp SPV pump at 5.5 kWh/m^2 daily solar radiation availability, the unit cost of CO_2 emissions mitigation is estimated at US$ 169.38/ton and US$ 405.06/ton in case of diesel and electricity substitution respectively.

Rezae and Gholamian [67] carried out a technical and financial study of photovoltaic water pumping system for irrigation of Gorgan farm fields in Iran using RET Screen software and concluded that installation cost of PV water pumping project is very high but considerable savings are observed. Foster et al. [68] surveyed 46 water pumping systems installed under Mexican Renewable Energy Program (MREP) – a collaborative program sponsored by the U.S. Agency for International Development (USAID) and the U.S. Department of Energy (DOE). The results obtained prove that the majority of systems were functioning after 10 years and have proven to be an excellent option to meet water pumping needs in rural Mexico where electrical grid services are not available. The average investment payback for the PV water pumping systems was found to be 5–6 years, with some systems reporting paybacks in half that time.

Fedrizzi et al. [69] identified the technological and policy issues related to PV water pumping systems for traditional communities like conception of the project, availability of water, system configuration, estimation of water demand, technology transfer process and project management. The authors reported that the photovoltaic pumping systems failure occurs because issues related to the local conditions and technology transfer methods are not being taken into account.

Meah et al. [70] highlighted the need for using PV pumping in drought prone states. Wyoming, Montana, Idaho, Washington, Oregon, and part of Texas in USA which could use solar PV water pumping systems to supply water to livestock in remote locations and presented the initiative of using PV pumping systems in western USA state Wyoming. The study analyzed the performance of 75 systems in operation and showed excellent performance and cost effectiveness besides benefit of reduction of carbon emissions.

The main findings of economic and environmental aspects of PV water pumping systems are summarized in Table 4.

Table 4
Economic and environmental aspects of PV water pumping systems.

S. no.	Reference	Country	Study type	Research findings
1	Odeh et al. [60]	Ireland	Economic viability	Mismatch between water demand and supply patterns have a major effect on economic viability of the PV pumping.
2	Jamil et al. [61]	India	Techno-economic analysis	Payback period of less than 4 years with huge savings over 16 years.
3	Hamidat [62]	Algeria	Economic analysis	PV surface pumps to supply water can contribute to socio-economic development in remote Sahara regions.
4	Kaldellis et al. [63]	Greece	Economic and environmental analysis	PV pumping systems are economical viable options for water consumption needs of remote communities.
5	Purohit and Kandpal [64]	India	Financial evaluation	PV pumping systems are viable option when sufficient incentives are provided by government.
6	Foster and Hanley [65]	Mexico	Economic analysis	Economically viable PV water pumping systems gained foot hold and changing the face of water pumping in Mexico.
7	Kumar and Kandpal [66]	India	Environmental and economic analysis	Capital cost of PV pump, its useful life, price of fuel substituted, and discount rate on the unit cost of $CO_{2.}$ emission mitigation are of importantance for solar pumping promotion
8	Rezae and Gholamian [67]	Iran	Economic analysis	Considerable savings are observed in PV water pumping system as compared to conventional systems.
9	Foster et al. [68]	USA	Rural water supply	Investment payback for PV water pumping systems is averaged about 5–6 years
10	Fedrizzi et al. [69]	Brazil	Irrigation	Negligence of local specificities and technology transfer methods cause PV water pumping systems failure.
11	Meah et al. [70]	USA	Rural water supply	PV water pumping systems reduce CO_2 emission considerably over its 25-year life span.

3.6. Impact of PV generator degradation on pumping system performance

PV modules are prone to degradation due to humidity, temperature, system bias effects and solar radiation. During prolonged outdoor exposure, the efficiency of a solar PV panel decreases continuously because the panel components age. Degradation in solar cell material affects the power output and hence has an impact on the performance of PV systems which is expected to operate reliably for at least 20–25 years. In order to justify the high initial investment in such systems, it is important to evaluate the long term reliability of PV modules that power such systems. Keeping this aspect in view a literature review of degradation analysis of different PV module technologies is presented in this section to identify the annual depletion rates in electrical parameters after long-term exposure for improving the performance of PV generator and hence water pumping.

Quintana and King [71] summarized several modes of degradation in field aged PV modules. Sastry et al. [72] tested crystalline silicon PV modules of 20 different manufacturers during long-term outdoor exposure under Indian conditions and found that only 17.6% of modules failed which suggested that majority of modules can function beyond the standard life time period. Skoczek et al. [73] studied five different PV technologies after an initial exposure of 130 sun hours. The CIS module is found to degrade by more than 20%, amorphous Si module degraded by about 60%, and a-SiGe module degraded by approximately 13%. The crystalline EFG-Si and mono-Si modules showed no degradation in performance. The experimental result shows the effectiveness and reliability of PV module performance.

Edson et al. [74] carried out a comparative study of four 3 kW grid-connected PV systems installed on the rooftop of a Test Centre in South Korea, for a period of 12 months exposure and concluded that the performance of PV system declined due to increased array losses, of about 14%, due to module deterioration and mismatch of PV subarrays. Machida et al. [75] studied outdoor exposure of six modules of a 50-kW array near Tokyo for more than 5 years and concluded that mono-crystalline silicon showed larger power decline as compared to multi-crystalline silicon.

Soa et al. [76] have shown that multi-crystalline silicon modules have smaller degradation rates than mono-Si modules and substantially lower rates than the a-Si modules. The degradation rates are found to be slightly below $0 \cdot 5\%$ per year in the temperate climate of Germany.

McMahon and Osterwal [77] reported that thin-film degradation rates are about 1% per year whereas to meet 25 year commercial warranty degradation rate of 0.5% per year is necessary. Dechthummarong et al. [78] studied degradation of an array of 32 modules after an exposure of 27 years under harsh conditions in hot-desert of Arizona and reported that more than one third of the modules were either non-functional or near non-functional with less than 30% of the original power, while the rest of the set exhibited a power degradation of 1.08% per year of average.

Carr et al. [79] evaluated the performance of five different technology PV modules from seven different manufacturers in Australia for 16 months of outdoor operation. The results indicated that mono and polycrystalline silicon PV modules show 2% power reduction per year whereas amorphous and CIS solar modules exhibited a significantly higher power reduction. Raghuraman et al. [80] found that mono-crystalline and polycrystalline silicon modules exhibited low power degradation (approx 0.5% per year) while a-Si multi-junction modules degraded more (1.16% per year).

Marion and Adelstein [81] showed that performance of PV systems reduced at a rate of 1% per year. Realini et al. [82] analyzed the performance of a 10 kW crystalline silicon PV system installed at Lugano, Switzerland after 21 years of operation and found 0.5% per year power degradation. Jordan and Kurtz [83] recently reviewed the degradation rates from the field testing studies carried out during the last 40 years and concluded that the average of power degradation rates is 0.8% per year. In another study Sastry et al. [84] showed that Cd–Te and mono-crystalline solar cell technologies are found to be more resilient to degradation than amorphous-silicon modules.

Sharma and Chandel [85] in a comprehensive review on the degradation of photovoltaic technology for long term reliability emphasized the need to develop location specific stringent and more quantitative qualification standards for PV module testing.

Understanding the degradation of PV generator modules of pumping system can lead to improve the performance of the pumping system. In a recent study Chandel et al. [86] have carried out degradation analysis of the PV generator of a 28 year old direct coupled mono-crystalline PV water pumping system installed at Hamirpur town in India which shows that after 28 years only 2 modules developed hot spots thus reducing the efficiency of the system. These degraded modules can easily be replaced by new modules to make PV pumping system functional.

4. Viability of PV pumping system technology

4.1. Initiatives in developing countries

The viability of PV pumping systems has long been evaluated since the late 1970s. One of the earliest viability assessment programmes for PV pumping systems was initiated by UNDP in 1978 in a project given by World Bank [87]. The program known as *Global Solar Pumping Project* was aimed at determining techno-commercial viability of solar pumps. In Phase-I of the project twelve pumping systems (one solar thermodynamic and rest PV type) was field tested in Mali, Sudan and Philippines in 1980. Three systems performed better than the rated value, two within 10%, and five significantly lower than the rated values. Two remaining systems failed to operate including the thermodynamic pump. Although the results were not encouraging, the study did demonstrate that the technology is promising provided enough research is done to improve the systems. As a result the Phase-II of the project was announced and 64 systems with improved specifications were tested. The performance of these systems was found to be improved but still required further research and development to improve the performance and reliability. It was found that PV pumping systems were economically viable in countries with high sunshine, having high diesel prices and all year round water requirements.

A Handbook on Solar Water Pumping was published by World Bank in 1984 which was further updated in 1986 and 1989-90. Similarly, a report on PV pumps was first published by Sandia National Laboratories in 1987 [88] with subsequent revisions in subsequent years, highlighting the benefits of PV pumping systems. A *Renewable Energy Water Pumping Systems Handbook* by Argaw [89] covering renewable based water pumping technologies was published by National Renewable Energy laboratory [NREL], USA in 2004. Gopal et al. [90] in a recent review have discussed the relevance renewable energy based pumping systems in present context.

PV systems are found to be more economically attractive as compared to diesel based pumping systems. The PV module and Balance of Systems (BoS) costs have declined significantly now since these viability studies were done. It is apparent that PV systems that are now available are far more reliable and cost effective than in early days. A report published by GIZ in 2013 reported a payback period for PV pumping systems in India of 4 years, with LCOE of Rs.8.60 (US$ 0.141) as compared to Rs. 13.90 (US$0.228) of diesel based pumping systems [91].

Durin and Margeta [92] studied the feasibility of PV generator for electric energy supply for water pumping in urban water supply system and have shown that PV water pumping can be effectively utilized either by using stand alone PV systems or in combination with other electricity supply systems for better reliability.

PV system viability is sensitive to the amount of insolation available and energy utilization. For example if the system's output is not fully utilized then the installation may not be financially attractive. PV is an attractive alternative for developing countries like India, China, other Asian and African countries as abundant insolation is available and significant rural population lives in remote areas.

4.2. Indian initiative on PV pumping

India has 26 million ground water pumps in agriculture farms which are run using electricity and diesel [93]. The power failure/ shortage and ever increasing diesel fuel costs affect agriculture production and irrigation of crops. The adoption of solar PV pumps can save considerable electricity and diesel subsidies being provided to farmers.

Solar pumping program in India was first started by Ministry of New and Renewable Energy (MNRE) in 1992 and during the 1992–2014 period, 13,964 solar pumps were installed in the country [94]. With the launch of Jawaharlal Nehru National Solar Mission (JNSSM) in 2010 by MNRE [95], a fresh thrust has been given to solar pumping program in India under which 3 billion rupees (US $49 million) have been allocated as subsidy to be provided to small farmers for the installation of PV pumps. During 2014–15, 17,500 solar-powered pumping systems are to be installed with a target of 1 million solar pumps for irrigation and drinking water purpose by the year 2021. The objective is to boost agricultural yield and reduce dependence on diesel for water pumping in the states including Rajasthan, Tamil Nadu, Andhra Pradesh, Uttar Pradesh, Maharashtra, Chhattisgarh, Madhya Pradesh, Bihar, Punjab, and Himachal Pradesh. The grants to farmers will cover 30% of the cost of solar water pumping system limited to Rs 57,000 (US$933) per kWp up to 5 kWp PV module capacity for irrigation and other purposes. The participating state governments will have to provide matching grant of at least 15 percent of the cost and the farmer has to be bear the remaining cost.

Indian government has provided guidelines [96] to the manufacturers of PV panels as per international standards with modern testing procedures, so as to ensure quality product with better performance and long life. Mono/multi-crystalline silicon PV modules as per IEC 61215 specifications or equivalent National or International/ Standards are to be used in solar pumps. The modules must qualify to IEC 61730 Part I and II for safety qualification testing. The efficiency of the PV modules should be minimum 13% and fill factor should be more than 70%.

The AC/DC motor pump sets suitable for PV water pumping system and AC–DC, DC–DC converters as per requirement are to be used.

MNRE has approved technical specifications of a solar powered pumps [96] which are given in Tables 5 and 6.

This initiative is expected to boost the solar water pumping in India. Similar strategy needs to be followed by other countries especially the developing countries. Bern University of Applied Sciences (BFH) in Switzerland developed a small power (40–120 W) photovoltaic water pump which is being produced in Bangalore, India under an International project and is being promoted among women in India for small irrigation [97].

Table 5
Technical specifications of a solar-DC motor pump system [96].

S. no.	PV DC motor pump set with brushes or brush less	Shallow well (surface) PV pumping system		Deep well (submersible) PV pumping system	
1	Parameter	Model-I	Model-II	Model III	Model IV
2	PV array (Wp)	1800	2700	3000	4800
3	Motor capacity	2 hp (1492 Wp)	3 hp (2238 Wp)	3 hp (2238 Wp)	5 hp (3730 Wp)
4	Shut off dynamic head (m)	15	25	70	70
5	Water output (l/day)	1,80,000	1,48,000	63,000	1,00,000
6	Total head (m)	10	20	30	50

Table 6
Technical specifications of a Solar-AC induction motor pump system [96].

S. no.	PV AC induction motor pump	Shallow well (surface) PV pumping system		Deep well (submersible) PV pumping system	
1	Parameter	Model-I	Model-II	Model III	Model IV
2	PV array(Wp)	1800	2700	3000	4800
3	Motor capacity	2 hp (1492 Wp)	3 hp (2238 Wp)	3 hp (2238 Wp)	5 hp (3730 Wp)
4	Shut off dynamic head (m)	15	25	70	70
5	Water output (l/day)	1,80,000	1,48,000	57,000	91,000
6	Total head (m)	10	20	50	50

Table 7
Current PV cell efficiencies measured under 1000 W/m^2 at 25 °C [104].

PV cell materials	Efficiency (%)
Silicon	
Si(crystalline)	25.6 ± 0.5
Si (multi-crystalline)	20.8 ± 0.6
Si (thin-film mini module)	10.5 ± 0.3
III–V cells	
GaAs (thin film)	28.8 ± 0.9
GaAs (multicrystalline)	18.4 ± 0.5
InP (crystalline)	22.1 ± 0.7
Thin-film chalcogenide	
CIGS (cell)	20.5 ± 0.6
CIGS (minimodule)	18.7 ± 0.6
CdTe (cell)	21.0 ± 0.4
Si (amorphous)	10.1 ± 0.3
Dye sensitized	
Dye	11.9 ± 0.4
Dye mini module	10.0 ± 0.4
Multi-junction devices	
InGaP/GaAs/InGaAs	37.9 ± 1.2
a-Si/nc-Si/nc-Si (thin film)	13.4 ± 0.4
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4

5. Material and efficiency advancement in photovoltaics

PV generator is the main and costly component of solar water pump therefore its efficiency improvement and cost reduction are important parameters for further promotion of PV pumping technology. Considerable advancements in the material and efficiency improvements of solar cells have taken place during recent years [98–101] which have been discussed in this section. Solar cells are being used in satellite and space craft applications since 1950s but oil crisis and growth of PV industry in early 1970s resulted in remote area applications for electricity supplies and water pumping also. The mono-crystalline silicon and multi-crystalline silicon wafer based solar cells are known as first generation technology [98]. Mono-crystalline solar cells are made of silicon wafers cut from a single cylindrical ingot of silicon. The main advantage of these cells is high module efficiencies. Multi-crystalline silicon solar cells are made by casting molten silicon into ingots, which crystallize into a solid block of inter-grown crystals. These cells are less expensive to produce than mono-crystalline ones, due to the simpler manufacturing process and lower purity requirements for the starting material but with lower efficiencies than mono-crystalline. The crystalline silicon PV technology is now well established and shares about 90% of the world's PV installations and more than 80% of the world PV industry is based on crystalline silicon wafer based technologies.

Thin-film solar cells are the second generation cells based on amorphous silicon/hydrogen alloys or polycrystalline compound. Amorphous silicon PV cells are made from a thin layer of non-crystalline silicon placed on a rigid or flexible substrate. These are relatively easy to manufacture and are less expensive than crystalline solar cells, but are less efficient.

Dye-sensitized solar cells also known as dye-sensitized nano-structured solar cells, mesoscopic injection solar cells; nano-solar cells have exhibited efficiencies up to 12% for small cells, and 10% for mini-modules. Inorganic–organic lead halide Perovskite materials have recently emerged as a promising next generation material for photovoltaic applications due to its high power conversion efficiency [102,103]. Perovskite cells are named after a mineral found in the Ural Mountains. Perovskite materials have been well known for many years, but the first solar cell reported in 2009 was based on a dye-sensitized solar cell with only 3.8% power conversion efficiency. The efficiency of Perovskite cells is now reported as 18%. The highest efficiencies reported for Perovskite solar cells so far have been obtained mainly with methyl ammonium lead halide materials.

A number of materials and methodologies have been used by researchers for producing low-cost but high efficiency solar cells in recent years. The current status (2015) of solar cell efficiencies measured under standard laboratory test conditions is given by Green et al. [104] which are summarized in Table 7.

The efficiency of average commercial wafer-based silicon modules has increased from 12% to 16% and CdTe module efficiency increased from 9% to 13% in the last decade. The laboratory cell efficiency is 25.6% for mono-crystalline and 20.8% for multi-crystalline silicon wafer-based technology. The highest efficiency in thin film technology under lab conditions is 20.5% for CIGS and 21% for CdTe solar cells which shows that there is further potential for improvement at commercial production level. III–V multi-junction solar cells have obtained about 40% efficiency [105].

Recent progress in CPV with high concentration multi-junction solar cells achieves 44.7% efficiency with module efficiencies up to 36.7% in laboratory at Concentrator Standard Test Conditions (CSTC) which results in considerable reduction in the use of semiconductor material resulting in a considerable growth of installations in recent years [106]. Gallium (Ga), indium (In), and germanium (Ge) with limited global availability are mostly used in current designs for III–V multi-junction cells employed in CPV.

Bifacial modules have a potential application in PV water pumping. Bifacial modules were investigated since 1960s for space and terrestrial systems, including concentrator applications; however, interest in bifacial PV modules has arisen in recent years. A bifacial module is capable of capturing light from the front and back surface of the module, thus reducing the cost of PV electricity by enhancing power per unit area on the front surface. Power gain of 50% has been reported as compared to a standard mono-facial module for non-concentrating configurations [107,108].

Advanced solar cell manufacturing methods like ion-implantation and hetero-junction technologies are used to produce high efficiency solar cells and bifacial solar cells. Due to improvements in manufacturing technology the cost of PV has reduced by 90% since the 1970s and is expected to reduce further.

6. Results and discussion

The results of the research work carried out by various authors on different aspects of solar pumping technology are summarized in the respective sections. However, some of the important results are discussed in this section as follows:

- PV water pumping systems have shown significant advancements in the last decade. The limitations in the design of solar pumps introduced in the early 1970s have now been removed. The use of electronic systems have further increased the output power, performance, reliability and overall efficiency of the system for drinking, irrigation and community water supply applications. The first generation PV pumping systems used centrifugal pumps driven by DC/AC motors with hydraulic efficiencies varying from 25% to 35% whereas second generation PV pumping systems use positive displacement pumps, progressing cavity pumps or diaphragm pumps with high hydraulic efficiencies of even 70%. Controllers are used for monitoring storage tank levels and pump speed. Maximum power point tracking (MPPT) technology is used to optimize water pumping.
- Direct coupled DC solar pumps without battery storage are still low cost, simple and reliable for small irrigation, sprinkler or drinking water supplies but cannot operate at maximum power point of PV generator. However, adding a maximum power point tracker (MPPT) and controls/protections can further improve the performance of such PV pumps.
- A number of simulation programs have been developed by researchers for the performance prediction of the PV water pumping system based on solar radiation data of a location which are found to be sufficiently accurate in evaluating the actual performance of solar pumps. These combined with optimization sizing techniques developed have resulted in the selection of various components and refinement of PV pumping technology by the manufacturers.
- The fluctuations in the solar irradiance, accumulation of dust on PV generator and high module temperatures also affect the performance of PV pumps like any other PV system. Spraying water on the PV modules results in cleaning the dust as well as cooling of modules improves the module efficiency and hence the water flow rate. These aspects need to be adhered to so as to improve the performance.
- The degradation analysis of PV modules of a solar pump is important to be carried out as it identifies the degradation mechanism. Field studies on PV systems carried out during last 40 years show that average power degradation in PV modules is 0.8% per year [83]. The power generated is reduced due to degradation of PV modules of the generator because of prolonged field exposure thus requiring selection of appropriate PV technology. Understanding degradation mechanism and estimating module lifetime are important research areas for PV water pumping also as at present not much attention is given to this aspect.
- PV generator is the main component of the solar water pump. Thus selection of suitable PV technology is essential for the performance and reliability of solar pumps. The use of solar cells with materials of high efficiencies will reduce the number of modules, installation cost and land required for installation thus bringing the cost of solar power down as compared to the cost of electricity from fossil fuels. Thus, even the expensive PV cell technologies with higher efficiency can be less expensive at the module or PV system level than based on lower efficiency cells.
- Efficiency of PV water pumping systems can be improved by optimum sizing, adding MPPT and controllers. Optimum PV array tilt angle is another important parameter for enhancing the performance of fixed PV generator which can be determined at monthly, seasonal and annual values for each location. The maximum solar radiation falling on panels using optimum tilt angle increases the output power from PV panels used in the system.
- Most of the PV pumping systems use two axis manual tracking which can increase the system efficiency up to 20%. The use of automatic sun tracking improves the pump efficiency but adds to the system cost considerably.
- The investment payback for PV water pumping systems is found to be 4-6 years, with some systems reporting paybacks in half that time. PV modules are now readily available in a wide range of sizes from several well established PV companies. The reliability of PV is such that 20 to 25-year power warranty is given by the manufacturers with life expectancies beyond 30 years. With decline in PV module costs, warranty period of 25 years and with incentives available for installing PV pumping systems in some countries like India the payback period is going to be reduced further.
- PV pumping is economically viable for water needs of remote communities. However, the mismatch between water demand and supply patterns has a major effect on economic viability of the PV pumping. Therefore the water pumping projects for community water supplies need to be carefully designed.

The main factors inhibiting widespread implementation of PV pumping technology are high initial capital cost and lack of awareness among users. The results of GIZ study [91] in Indian context show that the life cycle cost of a 746 W diesel pumping system for a ten year period is 35.79% more than that of a PV powered system of same capacity. The levelized cost of energy (LCOE) of a fuel free PV pumping system is found to be Rs. 8.60 (US $ 0.141) as compared to Rs. 13.90 (US$0.228) of diesel pumping system. The life period of diesel pump is about 10 years whereas the standard warranty period for PV modules is 25 years. As a result, PV can serve as a highly reliable and low maintenance system especially for water pumping applications. PV panels ranging from 60Wp to 500Wp are found to be suitable for meeting domestic water pumping requirements in residential buildings.

7. Conclusions

A review of current status of solar photovoltaic water pumping system technology research and applications is presented. The study focuses on update on solar water pumping technology, performance analysis studies carried out worldwide, optimum sizing techniques, degradation of PV generator supplying power to pump, economic evaluation, environmental aspects and recent advances in materials and efficiency improvement of photovoltaic technology and experience of using solar PV pumps worldwide. Based on the study main conclusions are as follows:

- PV water pumping technology is reliable and economically viable alternative to electric and diesel water pumps for irrigation of agriculture crops.
- PV water pumping for urban, rural and community water supplies and institutions, is another potential feasible sector but is not still widely utilized. The remote inaccessible locations with no grid electricity also need special attention. These sectors still depend on conventional electricity or diesel based pumping system resulting in increased recurring costs to the users.
- Keeping in view the high installation costs of solar water pumps especially for large irrigation and water supplies, more incentives are required to be provided by governments to make

the technology further attractive alternative to diesel and electrical water pumping.

- Factors affecting the performance and efficiency improving techniques, use of highly efficient PV modules including bifacial modules and degradation of PV generator are areas for further research for lowering the cost, improving the performance and enhancing pumping system life time.

Solar pumping is an attractive alternative for irrigation and rural, urban drinking water pumping applications in developing countries especially India, China, other Asian and African countries, keeping in view huge solar potential and the fact that significant rural population lives in the remote areas which requires water for drinking and irrigation of crops.

References

[1] Foster R, Majid G, Cota A. A test book of solar energy. Renew Energy Environ 2014 [accessed 07.06.14].⟨www.amazon.com/Solar-Energy-Renewable-Environment⟩.
[2] Rohit KB, Karve G, Khatri M. Solar water pumping system. Int J Emerg Technol Adv Eng 2013;3:225–59.
[3] Kou Q, Klein SA, Beckman WA. A method for estimating the long-term performance of direct-coupled PV pumping systems. Sol Energy 1998;64:33–40.
[4] Protoger C, Pearce S. Laboratory evaluation and system sizing charts for a second generation direct PV-powered, low cost submersible solar pump. Sol Energy 2000;68:453–74.
[5] Foster Robert, Cota Alma. Solar water pumping advances and comparative economics. Energy Procedia 2014;57:1431–6.
[6] Solar-module-price-trends. ⟨http://www.solarquarter.com/index.php/component/k2/item/452-solar-module-price-trends⟩ [accessed 19.01.15].
[7] Top 10 world's most efficient solar PV modules (Mono-Crystalline). ⟨http://www.solarplaza.com/top10-crystalline-module-efficiency/⟩ [accessed 09.01.15].
[8] ⟨http://us.sunpower.com/solar-panels-technology/x-series-solar-panels/⟩.
[9] Abouda S, Nollet F, Chaari A, Essounbouli N, Koubaa Y. Direct torque control – DTC of induction motor used for piloting a centrifugal pump supplied by a photovoltaic generator. Int J Electr Robot Electron Commun Eng 2013;7 (8):619–24.
[10] Chandrasekaran N, Thyagarajah K. Modeling and performance study of single phase induction motor in PV fed pumping system using MATLAB. Int J Electr Eng 2012;5(3):305–16.
[11] Nabil M, Allam SM, Rashad EM. Performance improvement of a photovoltaic pumping system using a synchronous reluctance motor. Electr Power Compon Syst 2013;41(4):447–64.
[12] Eker B. Solar powered water pumping systems. Trakia J Sci 2005;3:7–11.
[13] A solar choice for pumping water in New Mexico for livestock and agriculture. New Mexico State University's (NMSU) Department of Engineering Technology. ⟨www.engr.nmsu.edu⟩; 2014 [accessed 07.08.14].
[14] Gad HE. Performance prediction of a proposed photovoltaic water pumping system at South Sinai, Egypt climate conditions. In: Proceedings of the thirteenth international water technology conference. Hurghada, Egypt; 2009. p. 739–52.
[15] Katan RE, Agelidis VG, Nayar CV. Performance analysis of a solar water pumping system. In: Proceedings of the 1996 IEEE international conference on power electronics, drives, and energy systems for industrial growth (PEDES); 1996. p. 81–7.
[16] Loxsom F, Veroj PD. Estimating the performance of a photovoltaic water pumping system. Sol Energy 1994;52:215–9.
[17] Khan MTA, Ahmed MR, Ahmed SI, Khan SI. Design and Performance analysis of water pumping using solar PV. In: Proceedings of the international conference of developments in renewable energy technology (ICDRET); 2012.
[18] Mokeddem A, Midoun A, Kadri D, Said H, Iftikhar RA. Performance of a directly-coupled PV water pumping system. Energy Convers Manag 2011;52:3089–95.
[19] Kou Q, Klein SA, Beckman WA. A method for estimating the long-term performance of direct-coupled PV pumping systems. Sol Energy 1988;64:33–40.
[20] Hadj Arab A, Chenlo F, Mukadam K, Balenzategui JL. Performance of PV water pumping systems. Renew Energy 1991;18:191–204.
[21] Pande PC, Singh AK, Ansari S, Vyas SK, Dave BK. Design development and testing of a solar PV pump based drip system for orchards. Renew Energy 2003;28:385–96.
[22] Mohanlal K, Joshi JC, Kothari DP. Performance analysis of a directly coupled photovoltaic water-pumping system. IEEE Trans Energy Convers 2004;19:3.
[23] Alghuwainem SM. Performance analysis of a PV powered dc motor driving a 3 phase self-excited induction generator. IEEE Trans Energy Convers 1996;11:1.
[24] Benghanem M, Daffallah KO, Joraid A, Alamri and Jaber A. Performances of solar water pumping system using helical pump for a deep well: a case study for Madinah, Saudi Arabia. Energy Convers Manag 2013;6:50–6.
[25] Atlam O, Kolhe M. Performance evaluation of directly photovoltaic powered DC PM (direct current permanent magnet) motor – propeller thrust system. Energy 2013;57:692–8.
[26] Setiawan A, Purwanto DH, Pamuji DS, Nurul Huda N. Development of a solar water pumping system in Karsts Rural Area Tepus, Gunungkidul through student community services. Energy Procedia 2014;47:7–14.
[27] Reddy PKR, Reddy JN. Photovoltaic energy conversion system for water pumping application. Int J Emerg Trends Electr Electron 2014;10 (2):2320–69.
[28] Bhave AG. Potential of solar water pumping in India. Appl Energy 1994;48:197–200.
[29] Eyad S, Al-Soud S. Potential of solar energy development for water pumping in Jordan. Renew Energy 2004;29:1393–9.
[30] Alawaji S, Mohammed S, Rafique S. PV powered water pumping and desalination plant for remote areas in Saudi Arabia. Appl Energy 1995;52:283–9.
[31] Kaka MS, Gregoire MS. Photovoltaic water pumping system in Niger, application of solar energy, Chapter-7; p. 184–94. ⟨http://dx.doi.org/10.5772/54790⟩.
[32] Padmavathi K, Daniel A. Studies on installing solar water pumps in domestic urban sector. Sustain Cities Soc 2011;2:135–41.
[33] Badari Mahayana P, Sanjeeva Reddy BR, Prasad M, Sanjay D. Design & simulation of solar DC pump in Simulink. IEEE Trans 2013;978 (1):4673–6150.
[34] Ould-Amrouche S, Rekioua D, Hamidat A. Modelling photovoltaic water pumping systems and evaluation of their CO_2 emissions mitigation potential. Appl Energy 2010;87:3451–9.
[35] Maurya VN, Diwinder Kaur A, Maurya AK, Gautam RA. Numerical simulation and design parameters in solar photovoltaic water pumping systems. Am J Eng Technol 2013;1:01–9.
[36] Biji G. Modelling and simulation of PV based pumping system for maximum efficiency. IEEE Trans 2012.
[37] Jafar M. A model for small-scale photovoltaic solar water pumping. Renew Energy 2000;19:85–90.
[38] Flores C, Poza F, Narvarte L. A tool to widen the possibilities of PV pumping simulation. Int J Sustain Energy 2012;31:73–84.
[39] Velvizhi J, Subramanian DP. Performance enhancement of PV based water pumping system. Int J Innov Technol Explor Eng 2014;3(10):2278–3075.
[40] Wagdy R, Nourb MA. Optimum design of a photovoltaic powered pumping system. J Power Sources 1994;50:1–9.
[41] Argaw N. Optimization of photovoltaic water pumps coupled with an interfacing pulse width modulated dc/ac inverter power conditioning devices; 1994. p. 1165–8, (IEEE First WCPEC; December 5–9, 1994; Hawaii).
[42] Yahia B, Arab AH, Azoui B. Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept. Sol Energy 2011;85:288–94.
[43] Kaldellis JK, Spyropoulos GC, Kavadias KA, Koronaki IP. Experimental validation of autonomous PV-based water pumping system optimum sizing. Renew Energy 2009;34:1106–13.
[44] Zvonimir G, Margeta J. A model for optimal sizing of photovoltaic irrigation water pumping systems. Sol Energy 2007;81:904–16.
[45] Hamidat A, Benyoucef B. Mathematic models of photovoltaic motor-pump systems. Renew Energy 2008;33:933–42.
[46] Firatoglu Z, Yesilata B. New approaches on the optimization of directly coupled PV pumping systems. Sol Energy 2004;77:81–93.
[47] Cuadros F, Rodrıguez FL, Marcos A, Coello J. A procedure to size solar-powered irrigation (photo irrigation) schemes. Sol Energy 2004;76:465–73.
[48] Odeh I, Yohanis YG, Norton B. Influence of pumping head, insolation and PV array size on PV water pumping system performance. Sol Energy 2006;80:51–64.
[49] Ziyad M, Dagh er F. The effect of electrical array reconfiguration water pump on the performance of a PV-powered volumetric water pump. IEEE Trans Energy Convers 1990;5:4.
[50] Abdolzadeh M, Ameri M, Mehrabian MA. Effects of water spray over the photovoltaic modules on the performance of a photovoltaic water pumping system under different operating conditions. Energy Sources 2011;33:1546–55.
[51] Azadeh K. The effects of nominal power of array and system head on the operation of photovoltaic water pumping set with array surface covered by a film of water. Renew Energy 2010;35:1098–102.
[52] Abdolzadeh M, Ameri M. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. Renew Energy 2009;34:91–6.
[53] Joao VMC, Luis Felipe MT. Implementation of a high-efficiency, high-lifetime, and low-cost converter for an autonomous photovoltaic water pumping system. IEEE Trans Ind Appl 2014.
[54] Kim J, Kim C, Kim J. A regulated charge pump with a low-power integrated optimum power point tracking algorithm for indoor solar energy harvesting. IEEE Trans Circuits Syst 2011;58:12.
[55] Eduard M, Water PV. Pumping with a peak-power tracker using a simple six-step square-wave inverter. IEEE Trans Ind Appl 1997;3.
[56] Sako KM, Guessan YN, Diango AK, Sangare KM. Comparative economic analysis of photovoltaic, diesel generator and grid extension in Cote Di'voire. Asian J Appl Sci 2011;4(8):787–93.

[57] Lal S, Kumar P, Rajora R. Techno-economic analysis of solar photovoltaic based submersible water pumping system for rural areas of an Indian state Rajasthan. Sci J Energy Eng 2013;1(1):1–4.
[58] Kolhe M, Kolhe S, Joshi JC. Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India. Energy Econ 2002;24:155–65.
[59] Rehman S, Sahin AZ. Performance comparison of diesel and solar photovoltaic power systems for water pumping in Saudi Arabia. Int J Green Energy 2014. http://dx.doi.org/10.1080/15435075.2014.884498.
[60] Odeh, Yohanis YG, Norton B. Economic viability of photovoltaic water pumping systems. Sol Energy 2006;80:850–60.
[61] Jamil M, Ahmed SA, Rizwan M. SPV based water pumping system for an academic institution. Am J Electr Power Energy Syst 2012;1(1):1–7.
[62] Hamidat A. Simulation of the performance and cost calculations of the surface pump. Renew Energy 1999;18:383–92.
[63] Kaldellis JK, Meidanis E, Zafirakis D. Experimental energy analysis of a stand-alone photovoltaic-based water pumping installation. Appl Energy 2011;88:4556–62.
[64] Purohit P, Kandpal TC. Solar photovoltaic water pumping in India: a financial evaluation. Int J Ambient Energy 2011;26:135–46.
[65] Foster R, Hanley C. Life cycle cost analysis for photovoltaic water pumping systems in Mexico. In: Proceedings of the 2nd world conference on photovoltaic energy conversion. Vienna, Austria; 1998.
[66] Kumar A, Kandpal TC. Potential and cost of CO_2 emissions mitigation by using solar photovoltaic pumps in India. Int J Sustain Energy 2007;26:159–66.
[67] Rezae A, Gholamian A. Technical and financial analysis of photovoltaic water pumping system for Gorgan. Int J Cybern Inform 2013;2:2.
[68] Foster RE, Alma D, Ross MP, Avilez OM. Ten-year reliability assessment of photovoltaic water pumping systems in Mexico. Sandia National Laboratories; 2013.
[69] Fedrizzi MC, Ribeiro FS, Zilles R. Lessons from field experiences with photovoltaic pumping systems in traditional communities. Energy Sustain Dev 2009;13:64–70.
[70] Meah K, Fletcher S, Ula S. Solar photovoltaic water pumping for remote locations. Renew Sustain Energy Rev 2008;12:472–87.
[71] Quintana MA, King DL. Commonly observed degradation in field-aged photovoltaic modules. In: Proceedings of the 29th IEEE PVSEC. USA; 2002.
[72] Sastry OS, Saurabh S, Shil SK, Pant PC, Kumar R, Kumar A, et al. Performance analysis of field exposed single crystalline silicon modules. Sol Energy Mater Sol Cells 2010;94:1463–8.
[73] Skoczek A, Sample T, Dunlop ED. The results of performance measurements of field aged crystalline silicon photovoltaic modules. Prog Photovolt Res Appl 2009;17:27–40.
[74] Edson L, Ernest E. Assessing the reliability and degradation of photovoltaic module performance parameter. IEEE Trans Reliab 2004;53:1.
[75] Machida K, Yamazaki T, Hirasawa T. Secular degradation of crystalline photovoltaic modules. Sol Energy Mater Sol Cells 1997;47:149–53.
[76] Soa JH, Jung YS, Yu GJ, Choi JY, Choi JH. Performance results and analysis of 3 kW grid-connected PVsystems: Field Demonstration Test Center in South Korea. Renew Energy 2007;32:1858–72.
[77] McMahon J, Osterwald CR. Commonly observed degradation in field-aged photovoltaic modules. In: Proceedings of the 29th IEEE photovoltaic specialists conference. New Orleans; 2002. p. 1436–9.
[78] Dechthummarong C, Wiengmoon B, Chenvidhya D, Jivacte C, Kirtikara K. Physical deterioration of encapsulation and electrical insulation properties of PV modules after long-term operation in Thailand. Sol Energy Mater Sol Cells 2010;94:1437–40.
[79] Carr AJ, Pryor TL. A comparison of the performance of different PV module types in temperate climates. Sol Energy 2004;76:285–94.
[80] Raghuraman B, Lakshman V, Kuitche J, Tamizh Shisler W, Mani G, Kapoor H. An overview of SMUDs outdoor photovoltaic test program at Arizona State University. IEEE Trans 2006.
[81] Marion B, Adelstein J. Long-term performance of the SERF PV systems. In: Proceedings of the NCPV and solar program review meeting; 2003.
[82] Realini A, Bura E, Cereghetti N, Chianese D, Rezzonico S. Study of 20-year old PV plant. ⟨www.MTBF Project.com⟩; 2001 [accessed 08.06.14].
[83] Jordan DC, Kurtz SR. Photovoltaic degradation rates – an analytical review. Prog Photovolt: Res Appl 2013;1:12–29.
[84] Sastry OS, Chandel R, Singh RK, Stephen RB, Dash PK, Kumar R. Degradation analysis of different PV modules after prolonged field operation. In: Proceedings of the 26th European photovoltaic solar energy conference and exhibition. Hamburg, Germany; 2011. p. 3495–9.
[85] Sharma V, Chandel SS. Performance and degradation analysis for long term reliability of solar photovoltaic system: a Review. Renew Sustain Energy Rev 2013;27:753–67.
[86] Chandel SS, Nagaraju Naik M, Vikrant Sharma, Rahul Chandel. Degradation analysis of 28 year field exposed Mono-c-Si photovoltaic modules of a direct coupled solar water pumping system in western Himalayan region of India. Renew Energy 2015;78:193–202.
[87] Barlow Roy, McNelis Bernard, Derrick Anthony. An introduction and update on the technology, performance, costs, and economics. World Bank Technical Paper, vol. 168; 8213–21.
[88] Thomas MG. Water pumping: the solar alternative [Technical Report]. Sandia National Laboratories; 1987⟨www.snl.org⟩[accessed 08.08.14].
[89] Argaw N. Renewable energy water pumping systems handbook. NREL/SR-500-30481. ⟨http://www.osti.gov/bridge⟩; 2004 [accessed 06.07.14].
[90] Gopal C, Mohan Raj M, Chandramohan P, Chandrasekar P. Renewable energy source water pumping systems – a literature review. Renew Sustain Energy Rev 2013;25:351–70.
[91] Pullenkav Thomas. Solar water pumping for irrigation: opportunities in Bihar, Deutche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH, Indo-German Energy Programme. ⟨www.igenre.in⟩; 2013 [accessed 14.04.14].
[92] Durin B, Margeta J. Analysis of the possible use of solar photovoltaic energy in urban water supply systems. Water 2014;6:1546–61. http://dx.doi.org/10.3390/w6061546.
[93] India-plans-for-26-million-solar-water-pumps. ⟨http://spectrum.ieee.org/energywise/green-tech/solar/⟩ [accessed 08.05.14].
[94] Solar pumping programme for irrigation and drinking water. ⟨www.mnre.gov.in⟩ [accessed 25.09.14].
[95] JNN national solar mission. ⟨www.mnre.gov.in/solar-mission/jnnsm/introduction-2/⟩ [accessed 08.05.14].
[96] Technical specifications for solar photovoltaic water pumping systems. ⟨www.mnre.gov.in/file-manager/…/technical-specification_spwps_2013_14.pdf⟩ [accessed 08.05.14].
[97] Schuepbach E, Muntwyler U, Vezzini A, Müller A, Urena D. Introducing solar water pumps to female farmers in India. In: Proceedings of the 29th European photovoltaic solar energy conference and exhibition. ⟨www.pvtest.ch/…/7AV_6_51_SWP_ES_EUPVSEC14_20140917.pdf⟩; 2014.
[98] Green MA. Recent developments in photovoltaics. Sol Energy 2004;76:3–8.
[99] Green MA. Silicon photovoltaic modules: a brief history of the first 50 years. Prog Photovolt Res Appl 2005;13:447–55.
[100] Razykov TM, Ferekides CS, Morel D, Stefanakos E, Ullal HS, Upadhyaya HM. Solar photovoltaic electricity: current status and future prospects. Sol Energy 2011;85(8):1580–608.
[101] Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. Renew Sustain Energy Rev 2011;15(3):1625–36.
[102] Park NG. Perovskite solar cells: an emerging photovoltaic technology. Mater Today 2015;18(2):65–72.
[103] Jeon NJ, Noh JH, Yang WS, Kim YC, Ryu S, Seo J, et al. Compositional engineering of perovskite materials for high-performance solar cells. Nature 2015;517:476–80.
[104] Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED. Solar cell efficiency tables (Version 45). Prog Photovolt: Res Appl 2015;23:1–9.
[105] Morales-Acevedo A. Thin film CdS/CdTe solar cells: research perspectives. Sol Energy 2006;80(6):675–81.
[106] Yamaguchi M, Takamoto T, Araki K. Super high-efficiency multi-junction and concentrator solar cells. Sol Energy Mater Sol Cells 2006;90(18–19):3068–77.
[107] Hezel R. A novel high-efficiency rear-contact solar cell with bifacial sensitivity, high-eff. low-cost. Photovolt Springer Ser Opt Sci 2009;140:65–93.
[108] Guo Siyu, Walsh Timothy Michael, Peters Marius. Vertically mounted bifacial photovoltaic modules: a global analysis. Energy 2013;61:447–54.