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# Status of photovoltaic water pumping systems in Iran: A comprehensive review

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## ABSTRACT

This study investigates the current status of photovoltaic water pumping systems (PVWPSs) in Iran, a country endowed with significant solar irradiation potential, notably in its southern and central regions. Despite this potential, there is a scarcity of comprehensive studies on solar water pumping systems within the country. This purpose of this study is to conduct a thorough review of the existing literature to assess the state of solar water pumping in Iran. The adoption of PVWPS across various provinces demonstrates the system's versatility, proving effective in both highly sunny and less irradiated regions. Iran's widespread utilization of PVWPS is attributed to its ample irradiations, even in its northern areas, which possess lower solar irradiance levels. There are limited comprehensive studies encompassing technical, economic, environmental, and social aspects of solar PV water pumping projects in Iran. Most of the research has been conducted during the last few years, indicating an increased recognition of the possible advantages of this technology. Finally, this review provides valuable insights for researchers and farmers, showcasing the benefits of solar PVWPS. It sets the stage for further innovation and implementation in the country's agricultural landscape, emphasizing the need for continued exploration and adoption of this sustainable approach.

**Key words:** Iran, irrigation, photovoltaic systems, review, solar energy, water pumping

## HIGHLIGHTS

- Increased awareness reflected in recent research, providing insights for policymakers, researchers, and farmers.
- Limited research despite Iran's substantial solar potential.
- Growing interest in harnessing solar energy for sustainable agriculture.
- Adaptability across Iranian's provinces and sustained economic efficiency.
- Emphasis on the advantages of PV water pumping, encouraging further innovation in agricultural landscape.

## ABBREVIATIONS

| | |
|---|---|
| AC | alternating current |
| ADOPT | Adoption and Diffusion Outcome Prediction Tool |
| BLDC | brushless direct current |
| CAD | Canadian dollars |
| CFD | computational fluid dynamics |
| DC | direct current |
| EES | engineering equation solver |
| FOB | free on board |
| ha | hectare |
| hp | horsepower |
| IWR | irrigation water requirement |
| LCOE | levelized cost of energy |
| L | litre |
| m | metre |
| MPPT | maximum power point tracker |
| NASA | National Aeronautics and Space Administration |
| NREL | National Renewable Energy Laboratory |

| | |
|---|---|
| PCM | phase change material |
| PV | photovoltaic |
| PVWPS | photovoltaic water pumping system |
| PPA | power purchase agreement |
| SDG | sustainable development goal |
| W | Watt |
| WBG | World Bank Group |

## 1. INTRODUCTION

Water is essential for industrial and urban development. Water scarcity exerts adverse effects on the quality of life globally. Water stress has social, economic, and ecological ramifications, thereby posing significant challenges to sustainable development (Guo *et al.* 2022). Estimations indicate a projected twofold increase in energy demand by 2050 and a tripling of this demand by 2100 (Lewis *et al.* 2005). Consequently, numerous studies are dedicated to addressing water supply concerns for both residential and industrial applications. The imperative for energy has spurred innovations in harnessing various forms of renewable energy for domestic and industrial purposes. Solar energy has emerged as one of the foremost energy sources in recent years.

In recent times, PV solar energy has garnered growing interest, fuelled by the declining costs of PV panels, even as their efficiency continues to improve (Ray & Douglas 2020; Renewable Energy Agency n.d.). Figure 1 depicts the evolution of the levelized cost of energy (LCOE) over the decade 2010–2020 for various sources. Notably, in 2020, solar PV emerged as the most cost-effective technology when compared to other alternatives. Moreover, PV Magazine (Solar Module Prices Continue to Fall 2023) reported an overall average reduction of 25% across all module technologies since the start of the year 2023. The same magazine reported in October 2023 (Solar Module Prices Dive to Record Low 2023) record low prices of \$0.14/$W_p$ for Mono PERC modules from China. However, recently it was shown that the quality of PV panels has decreased considerably (Libra *et al.* 2023) and that this decline is more severe in harsh conditions like in deserts (Desai *et al.* 2022). The authors expressed that this could negatively impact the real lifetime of PV power plant projects. Solar water pumping, a prevalent application of PV systems in developing countries, holds significance as a benchmark for gauging both social and economic development (Abdolzadeh & Ameri 2009). The deployment of solar water pumping within the agricultural industry exhibits practical reliability, as it aligns the peak water demand with the highest solar energy availability during hot seasons (Chahartaghi & Nikzad 2021). In developing countries, agricultural production is critically reliant on a sufficient water supply, and consequently, its productivity can be adversely impacted if an adequate water supply is not ensured (Chandel *et al.* 2017). While most systems are fossil fuel-based, a solar water pumping system can significantly mitigate greenhouse gas emissions while maintaining low operation and maintenance costs. Nonetheless, the

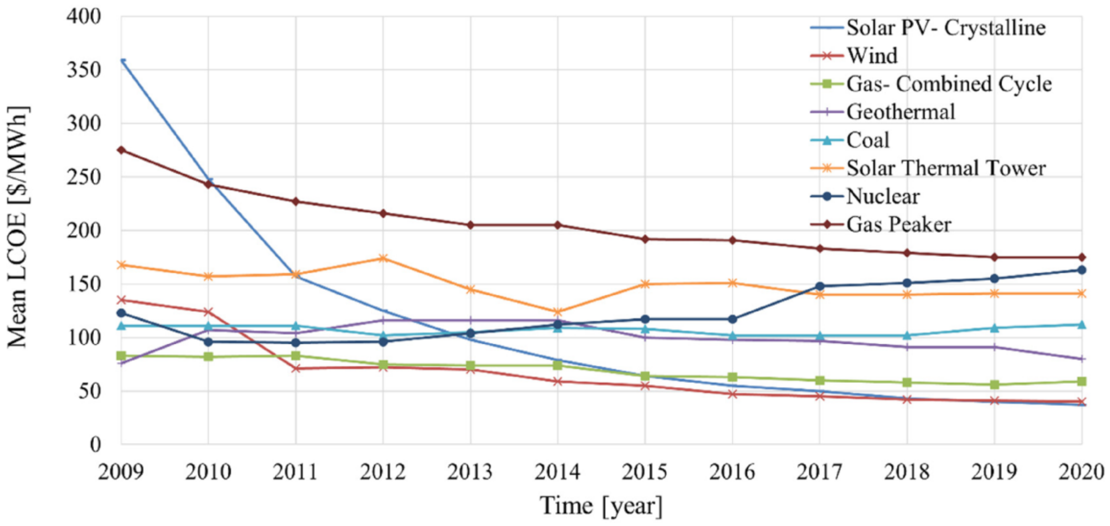

**Figure 1** | LCOE comparison for various energy generation technologies (reproduced from Ray & Douglas (2020)).

primary drawback of such a system resides in its substantial initial capital investment (Aliyu *et al.* 2018) especially in developing countries (Sontake & Kalamkar 2016).

## 2. IMPROVEMENTS IN THE EFFICIENCY OF PV SYSTEMS

As previously mentioned, the global demand for energy is on the rise, prompting numerous scholars and industries to seek ways to enhance the efficiency of their solar-based energy systems. Given the primary focus of this paper on solar PV renewable energy, this section provides a brief overview of methods employed to augment the efficiency of PV panels. A substantial body of research has been dedicated to exploring both active and passive cooling techniques. Shalaby *et al.* (2022) conducted an experimental study investigating the impact of water cooling on the rear side of PV panels in order to run a reverse osmosis system and preheat its feed water. PVC tubes were attached at the backside of a 250 W module providing direct contact between water and the panel. Coolant circulates with a constant mass flow rate of 0.15 kg/s. The location of the experiments is not explicitly mentioned in the article. However, maximum ambient temperature and solar irradiance at around noon on September 1st were shown to be 43.5 °C and 1,013 W/m$^2$, respectively. Their research revealed a notable maximum of 14.1% increase in power generation for the panel with cooling (from 173 W of the uncooled module to 197 W of the cooled one). The temperature drop was reported to range from 5 to 10 °C and 4 to 13 °C for the front and rear sides of the panel, respectively. Furthermore, the electrical efficiency improved from 17.4 to 19.8% through the implementation of this cooling technology. In another investigation, Gomaa *et al.* (2022) studied the impact of the coolant's mass flow rate on both the temperature distribution of the panel and the outlet temperature of the coolant for a PV thermal system. Their research also examined the influence of solar irradiation intensity on these parameters. To conduct their investigations, three-dimensional CFD model simulations of ANSYS 19.2 software were used. They considered two distinct cooling cross-fined channel box configurations, one thin (3 mm) and the other thick (15 mm) and scrutinized the thermal behaviour of the entire system. Ambient air and inlet coolant temperature were set to 25 °C and five water cooling flow rates of 0.5, 1, 1.5, 2, 3, and 4 L/min were considered at solar irradiances of 200, 400, 600, 800, and 1,000 W/m$^2$. By evaluation of the module temperature contours, they showed that the optimal coolant mass flow rate was 3 L/min for both channel box configurations at the maximum solar irradiance. Although the criteria for selecting the optimal mass flow rate was not explicitly mentioned in the paper, however, reaching a cool PV surface while keeping the mass flow rate as low as possible to avoid extra pressure drop penalties seems to be considered for selecting the optimum coolant mass flow rates. In another study (Maleki Ngo & Shahrestani 2020), researchers examined the influence of ambient temperature (25, 35, and 45 °C), solar irradiance (600, 800, and 1,000 W/m$^2$), and coolant inlet velocity (0.5, 0.7, and 0.9 m/s) on both the temperature distribution and efficiency of PV cells. A serpentine channel of the rectangular cross-section with a width of 5 mm and a height of 3 mm was used at the rear side of the panel. The pitch of the serpentine channel was 100 mm while the length and width of the panel were 850 and 541 mm, respectively. Therefore, nine cooling lines were incorporated at the backside of the panel. ANSYS CFX for modelling and ANSYS Mesh for grid generation were used. The findings demonstrated that the cooling channels employed at the rear of the PV cell naturally exhibited greater effectiveness under conditions of high solar irradiation and elevated ambient temperatures. However, they observed that increasing the mass flow rate of the coolant had a lesser impact at higher fluid flow rates. Hence, instead of conventional water coolants, nanofluids which are mixtures of base fluids with nanoparticles like silver (2022), silica (Cao *et al.* 2022), titanium or aluminium oxide (Ebaid *et al.* 2018), graphene nanoplatelets (Venkatesh *et al.* 2022), and magnesium oxide (Fakruddin Babavali *et al.* 2023) have been explored as an alternative to enhance the efficiency of cooling in PV or PV thermal systems. In addition to the active cooling methods discussed earlier, passive cooling techniques have also been the subject of numerous studies. Zhou *et al.* (2022) conducted research in which they employed rectangular wing vortex generators installed on the rear of the panels to augment the heat transfer rate from the cell under natural convection conditions (no wind flow over the panel). They conducted their study both numerically, using computational fluid dynamics, and experimentally, employing particle image velocimetry. They showed that the use of these vortex generators can decrease the panel temperature by 2–3 °C and that the aerodynamic geometry of these vortex generators can considerably alter the form of the vortices and consequently affects gaining a uniform cooling pattern. The utilization of phase change materials (PCMs) is one of the passive methods that gained attraction in recent years. They act as thermal storage and can absorb considerable amounts of heat from PV panels during the daytime and undergo a phase change. PCMs can be the only cooling technique used like the utilization of paraffin wax RT-42 with three different thicknesses of 1, 2, and 3 cm attached to the back sheet of a PV panel (Maghrabie *et al.* 2023). In this study, four different tilt angles of 15, 20, 25, and

30° were considered for two similar PV panels with nominal power generation of 40 W, one reference ($PV_r$) and the other one equipped with PCM (PV-PCM). The tests were done in the hot climate of Gena City in Egypt. It was concluded that the upper side of the panel had higher temperatures due to PCM melting and the formation of a vacuum area with no cooling. Specifically, 17.1, 15.7, and 13.2% higher temperatures at the upper side of the PV-PCM at PCM thicknesses of 1, 2, and 3 cm, respectively, for a tilt angle of 15°. In addition, it was shown that the electrical efficiency of PV-PCM with maximum PCM thickness (i.e., 3 cm) was improved by 14.4% leading to 15.8% more output power production at an optimal tilt angle of 30° compared to $PV_r$. PCMs were also simultaneously employed with other cooling techniques like the utilization of PV panels with plates equipped with ribs or dimples as another passive method to enhance heat transfer rates (Abo-Elnour *et al.* 2023). In this study, ANSYS 2020 Fluent was used to evaluate cell temperature and electrical efficiency of bifacial PV panels at three different configurations: first, a PV panel with a single PCM (RT-35), second, a ribbed unit with two PCMs (RT-27 and RT-35), and third, a bifacial panel with no cooling system. L-shaped mirrors were used to reflect the irradiation to the bottom cells. Three different solar irradiances of 800, 1,000, and 1,200 $W/m^2$ were considered. The schematic of the system and the three mentioned configurations are shown in Figure 2. The novel multiple PCM model showed around 13 °C reduction in its cell temperature compared to PV without cooling while its efficiency increased to 16.68% with respect to the 15.5% efficiency of PV with no cooling system.

In addition to cooling PV panels, optimizing the position of PV panels relative to the sun's position significantly impacts system power generation. The tilt angle has been a subject of investigation in numerous studies. Mamun *et al.* (2022) conducted experimental research assessing the impact of tilt angle on PV module performance under two conditions: constant solar irradiation with varying tilt angles and constant tilt angles with varying solar irradiation intensity, conducted in both outdoor conditions in Kuala Lumpur with latitude of 3.117° N and longitude of 101.667° E and indoor settings at Solar Thermal Research Laboratory of University of Malay. Their evaluation covered parameters such as temperature of cell, short-circuit current, open-circuit voltage, output power, and efficiency. It was shown that cell temperature increases by 7.5 and 5.7 °C for an irradiance increment of 100 $W/m^2$ at indoor and outdoor conditions, respectively. Furthermore, based on the outdoor experiments, the optimal tilt angle for Malaysia was shown to be around 15°. In a study conducted by Liu *et al.* in China (Liu *et al.* 2022), satellite data from 133 stations were utilized to evaluate traditional latitude-based models in regions characterized by significant climate variations. These data were used to estimate the diffuse fraction through Boland–Ridley–Lauret model (Ridley *et al.* 2010). This is a generic model for diffuse solar fraction estimation through global radiation. This model was shown to perform better especially at northern and southern hemisphere locations although it can be utilized as a universal model. The research of Liu *et al.* (2022) highlighted that the optimized tilt angle of panels is highly associated with diffuse fraction and latitude with correlation coefficients ($R$) of 0.8 and 0.86, respectively. They also mentioned that on average, PV panels with optimal tilt angle can produce 13.7% higher power compared to panels with no tilting.

In addition to the previous methods, enhancing power generation and efficiency also involves cleaning and dust removal processes of PV panels. Recently, Zarei *et al.* (2022) studied the impact of key factors, like relative humidity, rainfall, and

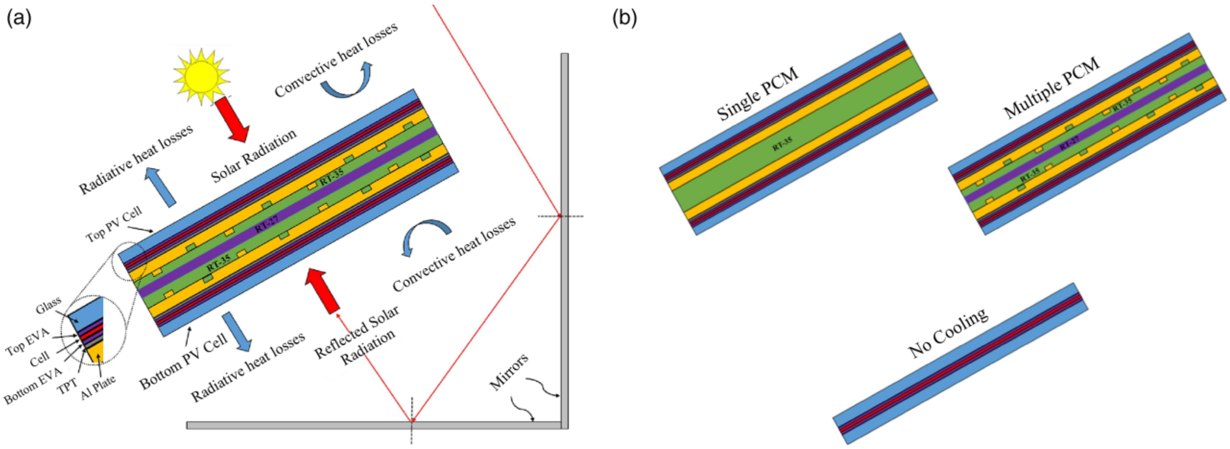

**Figure 2** | (a) Schematic of bifacial PV-PCM system and (b) three different PV configurations.

gravity on PV dust accumulation. They compared the decrease in power production capacity of PV panels in several locations worldwide due to dust deposition. Furthermore, they reviewed studies that utilized artificial particles generated from sources of pollution including industrial pollutants and the smoke of vehicles. Salamah *et al.* (2022) reviewed the effect of various climates on dust accumulation and PV performance in different regions of the world. It was concluded that shading or dust accumulation on PV modules decreases received irradiance and simultaneously elevates the PV cell temperature resulting in a reduction in the module's open-circuit voltage. In addition, the presence of dust on the surface causes a decrease in both module's short-circuit current and transmittance. The degree of this decrease is influenced by factors such as the concentration of particles with a maximum size of 10 μm ($PM_{10}$ concentration), dust loading, tilt angle, and particle concentration. Fan *et al.* (2022) evaluated the correlation between dust accumulation on PV modules and its efficiency for energy conversion by using CFD. ANSYS Fluent 15.0 was used as the modeller and ICEM was applied for domain grid generation. They employed the realizable $k$-$\varepsilon$ model and the discrete phase model (DPM) for the turbulent flow and dust deposition estimation, respectively. Three different wind speeds of 1.3, 2.6, and 3.9 m/s and four tilt angles of 5°, 15°, 30°, and 45° were considered. In addition, the dust particle diameter ranged from 1 to 300 μm. The findings reveal that the spiral vortex which is formed by dust particles becomes more prominent and gradually disperses with an increase in tilt angle. The vortex's length and angle at the rear side of the panel peak at a wind velocity of 3.9 m/s and a tilt of 45°. For the dust particle diameter less than 120 μm, wind speed exerts the maximum effect on the PV panels' conversion efficiency, demonstrating a linear relationship with deposition time. The increment of the diameter of the dust particle and wind velocity results in an increase in the conversion efficiency loss, reaching a maximum of 72.9% loss for the PV panels. Panidhara & Ramamurthy (2021), an experimental laser *in-situ* thickness measurement technique was developed to evaluate the correlation of PV panel efficiency with dust accumulation. It was revealed that a dust layer with a thickness of 500 μm can increase the temperature of the PV panel by 2 °C, leading to a reduction in photocurrent and a 50% reduction in the panel's conversion efficiency. They concluded that as the dust thickness rises, the infrared radiation transmittance increases which consequently leads to the degradation of the panel. Ekinci *et al.* (2022) used three different chemical solutions to evaluate the performance improvements of PV panels cleaned by a robot manufactured by means of 3D printing technology. The robot is equipped with in-line pressurized water-spraying fogging nozzles. The experiments were done in Adana City, Turkey. The impact of dust accumulation on short-circuit current and open-circuit voltage of five 50 W panels with different cleaning conditions of dust, solution 1 (2-propanol), solution 2 (ethanol), solution 3 (acetone), and water were evaluated. The three solutions were all 5% v/v. It is worth noting that the contact angle values acquired were 53.3°, 57.4°, and 60.2° for Solutions 1, 2, and 3, respectively. These values were below 90°, signifying the successful wettability properties of the solutions. It was revealed that the output power has risen by 15, 14, and 11% when cleaned with Solutions 1, 2, and 3, respectively.

Furthermore, improving the efficiency of the entire PV system, including inverter, battery, etc., was also the subject of many studies. For example, Ketjoy *et al.* (2021) studied three parameters affecting the efficiency of PV inverters. The first parameter was the duration of operation and the investigation of an inverter that worked for 4 years showed that its efficiency decreased negligibly from 91% of the manufacturer's specification of 90%. This was due to the cool temperatures of the storage room where the inverter was operating. The second factor was the type of PV panel that was connected to the inverter, and it was shown that the type of panel has the least effect. In fact, the power input from the PV affects the efficiency of the inverter and it was revealed that inverters connected to a p-Si PV panel had a maximum efficiency of 91%. Finally, the last factor was the irradiance level, and it was shown that inverters work at their maximum efficiency of 90% for irradiances higher than 350 $W/m^2$. In another recent study (Suriyachai *et al.* 2024), a comprehensive evaluation of the performance optimization of solar PV water pumps in Phayao, Thailand was provided. Response surface methodology (RSM) was used, and the study evaluates the effect of temperature, solar irradiance, and voltage on the pumping efficiency. The research highlights the solar water pump's potential as a sustainable, cost-effective solution for agriculture in isolated regions while notable improvements occur in performance under specific environmental conditions. In addition, the study applies a social return on investment (SROI) analysis, offering a holistic view of the economic, social, and environmental benefits of implementing PVWPS in remote areas. This investigation not only considers the technical feasibility but also the broader societal impacts, marking a significant contribution to the field of renewable energy and sustainable agriculture. It is important to note that the efficiency of the PV panel or the entire system is not the only objective of the studies, and some researchers explored the economic aspects of projects like minimizing the LCOE (Osmani *et al.* 2021). This concludes our review of methods for increasing the efficiency of solar PV systems; the following sections will focus on solar water pumping systems.

## 3. SOLAR PV WATER PUMPING SYSTEMS

One of the prominent usages of solar energy lies in solar-based water pumping systems. Given the critical importance of energy supply and the global issue of water scarcity, solar water pumping has gained attention, even from organizations like the World Bank Group (WBG). In a report by the WBG (Welsien *et al.* 2018), an extensive investigation into the fundamentals of solar water pumping is conducted, encompassing aspects such as design, sizing, key components, installation, operation, maintenance, and life cycle cost assessment. Another notable report forming basic information, conducted by Argaw *et al.* (2003) presents a comprehensive study for selecting the most suitable energy system for water pumping in rural areas. This study introduces a methodology for cost-effective and efficient selection of the appropriate pump and energy source, considering both renewable and non-renewable energy resources. Affiliated with the National Renewable Energy Laboratory (NREL), this research addresses all technical aspects of water pumping, involving solar PV and diesel technologies. This report aims to compare power sources for rural water pumping, focusing on applications like water supply, irrigation, and livestock watering. The goal is to show how collaboration between governments, NGOs, and institutions can raise the sustainable utilization of renewable energy systems. In another study, Chandel *et al.* (2015) performed an in-depth literature review on solar pumping technology, while evaluating research gaps and considering economic and environmental aspects. Their study also emphasized the performance assessment of PV systems, including sizing, power degradation in pumping systems, PV material characteristics, and efficiency enhancements. They declared that the majority of PV pumping systems employ manual tracking along two axes, a practice that is able to enhance the efficiency of the system by up to 20%. The payback period for PVWPS typically ranges from 4 to 6 years, and some systems have reported even shorter payback periods. PV panel manufacturers provide a 20- to 25-year power warranty due to the reliability of the panels, with real lifespans of more than 30 years. They concluded that as PV module costs decrease and incentives for PV system installations, particularly in India, become available, the payback period is anticipated to further decrease.

In another study by Bhayo *et al.* (2019), a solar PV system is explored for generating the required electricity for a rural household, with a focus on utilizing excess power for water pumping. This study is conducted in the region of Malaysia, considering specific electricity consumption patterns that account for a daily load demand of 3.2 kWh per day. To ensure system reliability during cloudy or rainy conditions or at night, a bank of batteries is integrated, and charged during surplus electricity production. A MATLAB code is developed, and the study is conducted over a 30-day period, using real-time weather data, as shown in Figure 3. The system includes PV panels, battery banks, a motor-pump unit, and inverters, as illustrated in Figure 4. The study evaluates the LCOE, conducts technical assessments of the system, and explores sizing considerations. The cost of energy for varying numbers of PV panels and battery capacities were evaluated. Furthermore, the study investigates the volume of water that can be pumped using excess power. The research identifies that low irradiation levels during certain hours can significantly impact system sizing. It was mentioned that for a loss of power supply probability (LPSP) of 0, the number of PV panels depends on the day with the worst radiation condition. A system consisting of 8 PV panels with a

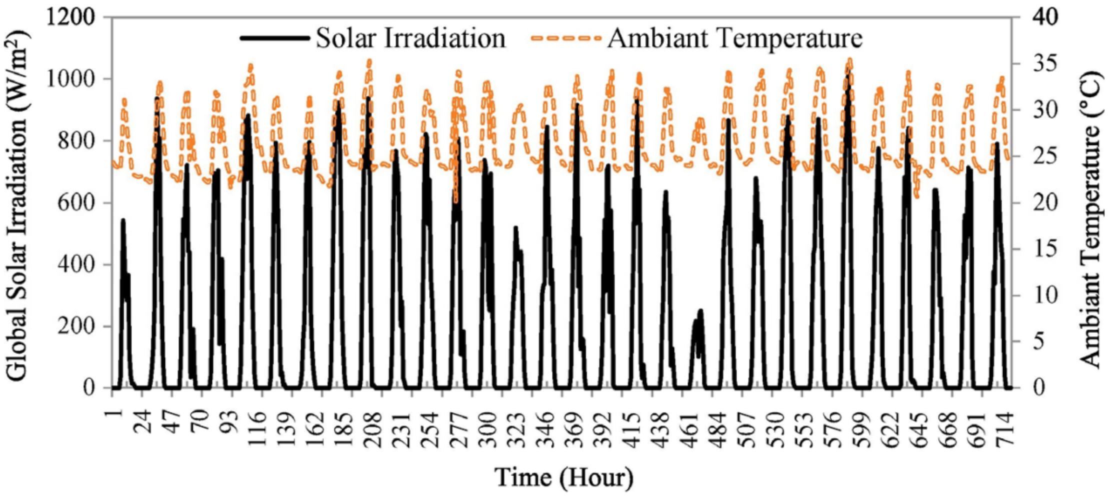

**Figure 3** | Solar irradiation and ambient temperature for a 30-day period (Bhayo Al-Kayiem & Gilani 2019).

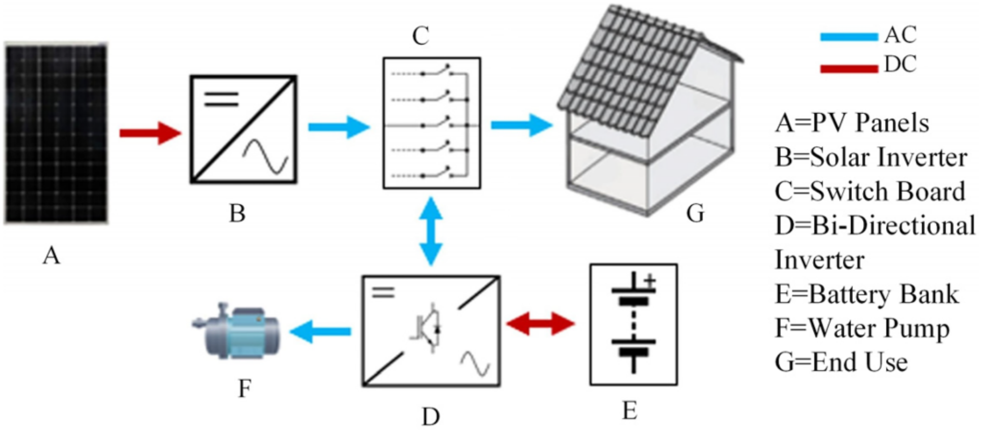

**Figure 4** | Design model of PVWPS of reference (Bhayo Al-Kayiem & Gilani 2019).

total power capacity of 2.44 kW and an installed battery capacity of 3.533 kWh was suggested for meeting the mentioned daily load demand. The proposed system requires about 16 m² of installation space and can pump 363 m³ of water per day to an elevation of 6.0 m by using the excess power. The levelized cost of electricity for this system was 0.3750 $/kWh.

Hadj Arab *et al.* (2004) studied the estimation of loss of load probability (LLP) of a PVWPS. They considered a constant profile (i.e., total 6 $m^3$ of water consumption per day) with a two-day autonomy tank and used a centrifugal pump and presented a technique for LLP calculation as well as a tool for system sizing. The method allows the creation of LLP maps using meteorological data. They validated the models developed for PV arrays and motor-pump units experimentally. They selected four sites in Algeria as case studies: Algiers, Bechar, Oran, and Tamanrasset. Bechar and Tamanrasset are in the Sahara region of the country and these regions represent 80% of Algeria with arid or semi-arid climates. The approach uses a computer program employing mathematical models from actual measurements of a motor-pump and PV system. The PV array model considers the non-linear characteristics of the irradiations. Results revealed that southern locations need smaller PV arrays due to higher solar radiation, while northern locations are less sensitive to sizing errors. They expressed that the sizing and LLP estimation methods can be applied for every location beyond Algeria. In another study conducted by Gualteros & Rousse (2021), a software program was developed using Python to aid individuals in rural areas with limited knowledge of water pumping and solar energy. This software assists users in making decisions and analysing the sizing of PV panels and reservoirs, ultimately improving their access to water resources. The study introduced the concept of water shortage probability (WSP) as a tool for evaluating system sizing. The overall procedure of sizing, optimization, and cost evaluation of the study is shown in Figure 5. The research findings revealed that the most critical parameter in determining

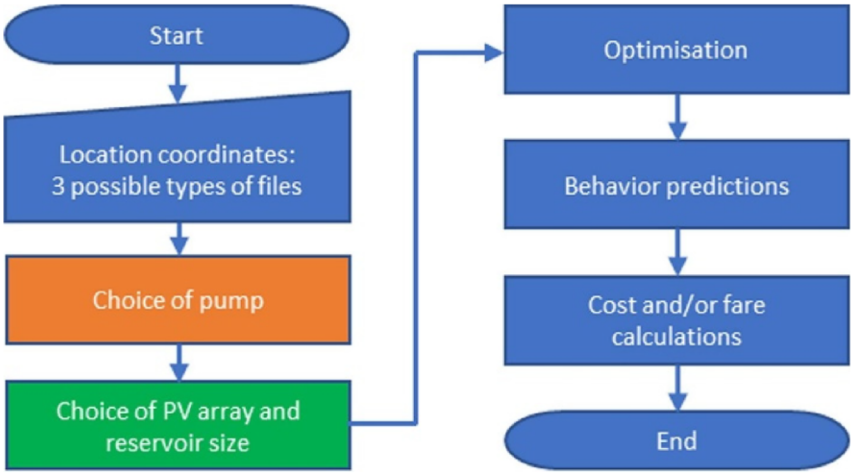

**Figure 5** | Schematic of the methodology of the study (Gualteros & Rousse 2021).

the size of a water pumping system is the willingness of water users to tolerate periods of limited access to water. Figure 6 illustrates the WSP for a system over the course of a year. It is evident that water shortages occur in November, December, and mid-January, with a maximum of 0.5% in early December. The study concluded that even a slight improvement in the reliability of water access could potentially lead to a doubling in the required size of PV panels or water reservoirs.

In a study conducted by Santra (2021), solar water pumping for a farm in a hot arid area of India, western Rajasthan, was examined through pressurized irrigation systems. This region benefits from 5.75 kWh/m$^2$/day solar irradiation which is higher than the annual average of India (equal to 5.4 kWh/m$^2$/day). Alongside technical considerations, the study also assessed different aspects of PVWPS by micro-irrigation techniques including drippers, mini, and micro sprinklers. The research highlighted a common practice in India, where 3-hp or 5-hp high-capacity water pump systems are typically used for farm irrigation, often leading to a strain on water resources. However, in this study, a 1-horsepower (hp) solar water pumping system was specifically investigated, representing a feasibility study for low-power water pumping in support of small farms. The results indicated that solar systems exhibit significantly more favourable environmental impacts compared to conventional systems. Specifically, when considering carbon footprint (measured in kg $CO_2$-equivalent per hectare-millimetre), the solar system yielded emissions of 0.009 kg, whereas grid-connected electric pumps and diesel pumps produced 1.214 and 0.382 kg of emissions, respectively, for 1 hp pump capacity and 20 m of total head. In terms of kg $CO_2$-equivalent per kWh, these values would be 0.011, 1.439, and 0.743 for these three types of irrigation systems, respectively. In general, this study showed the feasibility of using low-power irrigation system for small-scale farms in the western Rajasthan in water scarcity situation of the region. In another study by Vishnupriyan *et al.* (2022), the impact of varying tilt angles on the performance of a solar water pumping system was investigated for irrigation as well as drinking water supply. The researchers employed PVsyst software for their numerical assessments, considering four different tilt angles of 8, 15, 30, and 45°. They evaluated the system's performance in terms of solar production, performance ratio, and energy loss. The findings indicated that the system achieved its optimal performance at a 30-degree tilt angle. Notably, the optimization of tilt angles has been a subject of investigation by numerous researchers, with the choice of the most suitable angle depending on the users' objectives to get annual

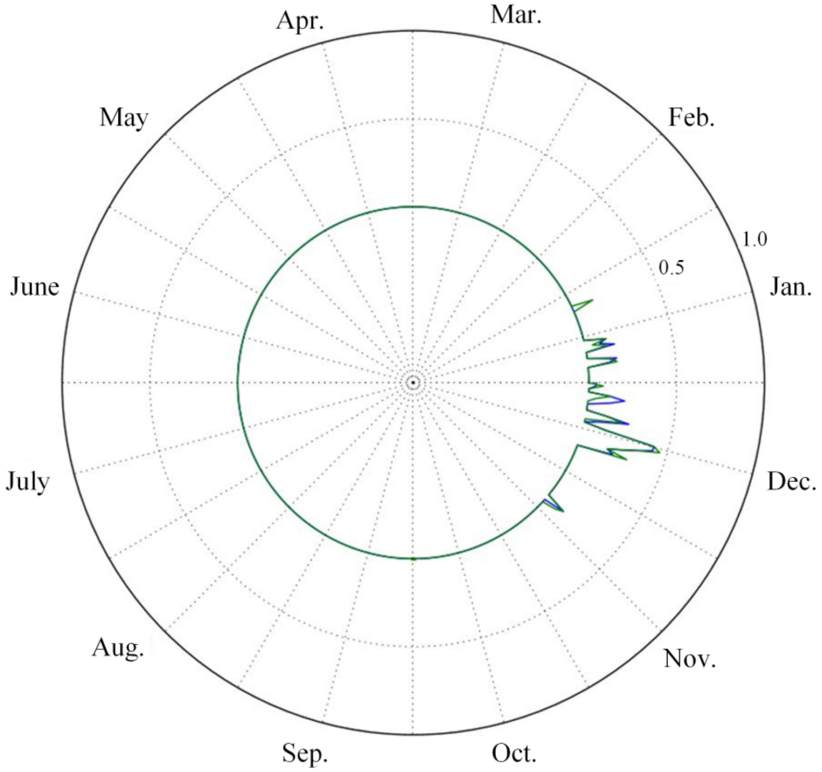

**Figure 6** | Distribution of water shortage probability during a year (Gualteros & Rousse 2021).

or seasonal maximum gain and the intended application of the solar system. In a research effort conducted in Australia by Powell *et al.* (2021), the adoption of renewable solar water pumping technology by sugarcane farmers was studied. The survey utilized the Adoption and Diffusion Outcome Prediction Tool (ADOPT), a numerical tool designed for practical use. This tool boasts over 1,000 users across 43 countries (*CSIRO, Australia's National Science Agency and Innovation Catalyst* n.d.). The survey consisted of different questions, addressing common opinions and the underlying reasons. Additionally, the study examined the constraints affecting the adoption of solar PV systems by farmers. It was concluded that the adoption of a solar system for irrigation by Australian farmers is influenced by various factors, including risk factors, financial status, relative advantages, and environmental benefits, among others. The findings from this study provide valuable insights for governments and policymakers regarding trends in farmers' adoption of solar systems.

In a study by Ashraf & Iqbal (2020), two solar water pumping systems were compared in weather conditions of Rahim Yar Khan, Pakistan with global horizontal irradiance ranging from 3.6 to 7.26 kWh/$m^2$/day. The goal of the study was to provide water for irrigation of a Rhodes Grass farm of around 97 ha. One system incorporated a battery bank, while the other featured a cylindrical water tank. HOMER software was employed for system design, sizing, and steady-state analysis, while MATLAB/Simulink was used for dynamic simulations of a solar water pumping project of 25 years lifetime. The sizing of both systems revealed that for the first configuration (i.e., system with battery), 73.8 kW of PV panel, and 450 Trojan SAGM 12 V 105 Ah battery is required to run a motor of 11-kW. On the other hand, for the other configuration, a 72.3 kW PV panel is needed to power a 55-kW motor while the capacity of the water tank was calculated to be about 4,900 $m^3$. The economic evaluation, based on similar pumping performance, revealed that the solar water pumping system designed with a water tank presented a cost-effective solution in comparison to its battery bank counterpart. Specifically, the system with a battery bank had a net present cost of $273,570, while the system with a water tank resulted in a net present cost of $158,399. In another study, Ghoneim (2006) conducted an optimization study on a direct-coupled PVWPS in 2006. The performance of this system was evaluated from both technical and financial perspectives for a residential complex in remote areas of Kuwait, accommodating 300 individuals. The region has high radiation of about 6 sun-hours per day. The analysis considered a water consumption rate of 40 L per day per person, resulting in a daily water pumping commitment of 12 $m^3$. A computer program was developed to model the PV panel, MPPT, DC motor, centrifugal pump, and storage reservoir. The evaluation encompassed the sizing and orientation of the PV system, as well as system performance. They used a motor-pump model developed by Eckstein (1990) and Al-Ibrahim (1996). In their model, the pump's performance can be estimated by applying the affinity laws, which establish a correlation between the pump speed, flow rate of fluid, head, and power. Finally, the life cycle cost method was used to assess the financial feasibility of the system. The financial assessment indicated that the capital cost of the PVWPS was lower than that of a conventional diesel-based pumping system while considering the high prices of PV panels at the time of the study. It was concluded that it was expected that the price of water pumps and PV panels decrease each year making the PV pumping systems more feasible. In 2020, on-farm applications of solar PV systems were studied by Gorjian *et al.* (2020). They concluded that more technical and socioeconomical research is needed to increase PV system adoption in the farming industry. They summarized the advantages and disadvantages of PV systems in the agriculture sector in Table 1.

In addition to the previously mentioned techniques, controlling strategies in solar systems are of high importance to maximize power generation. In this regard, Ammar *et al.* (2022) employed a DC-DC converter accomplished as maximum power

**Table 1** | Privilege and drawbacks of PVWPS adoption in the agriculture sector (Gorjian *et al.* 2020)

| **Advantages** | **Disadvantages** |
|---|---|
| Environmentally friendly | Reduced efficiency due to temperature increment of panels |
| Ease of use in a hybrid model with conventional technologies | Being unpredictable and requiring storage options |
| Being noise-free | High investment costs |
| No inconformity between solar generation and consumption | High payback periods with a low benefit-to-cost ratio |
| Suitable for remote areas with limited or no access to fuel or grid electricity | PV cleaning requires water, which is scarce in arid areas |
| Adoptable in versatile combinations | Low energy and output power |
| Continuously reduced unit prices through mass production | Operation control and optimization as major research areas |

point tracking in a battery-less PVWPS. They utilized a brushless direct current (BLDC) motor to maximize the utilization of power generated by the array and to increase the reliability of the system. To improve control performance when there is partial shading, the authors suggested an MPPT strategy based on Cuckoo Swarm Optimization (CSO) and Perturb and Observe (P&O) techniques by using MATLAB/Simulink. P&O is one of the most common schemes used for maximum power point tracking (Zaheeruddin *et al.* 2016). The investigation of Ammar *et al.* revealed that the P&O method was not successful in searching the global maximum power point. In contrast, the CS approach successfully identified the global peak while evading local maxima at partial shading conditions. Furthermore, the CS technique showed faster convergence and reduced oscillation around the maximum power point.

It is worth mentioning that there are numerous studies investigating different solar water pumping systems all over the world. For instance, in a study by Shahverdi *et al.* (2021), an organic Rankine cycle was employed to generate the necessary electricity for operating a pump responsible for water supply to a 3-ha farm located in the southeastern part of Zanjan province. To provide the required heat for the Rankine cycle, a parabolic trough concentrator was utilized. The study explored eight different organic fluids, and the mathematical model was solved using EES Software. The results obtained from the numerical study were subsequently validated through experimental investigations (Kasaeian *et al.* 2015). The findings of the study indicated that using Methyl Diethanolamine as the working fluid yielded the best performance, achieving a system efficiency of 12.19%. However, it was observed that the payback period for the system was relatively high, calculated at 18 years. In our review of PVWPS, we emphasize the pivotal role of solar energy in advancing sustainable agricultural practices and water management. The potential of solar energy extends beyond irrigation to encompass various other applications, underscoring its versatility and significance in renewable energy research. For example, Alhuyi Nazari *et al.* (2023) investigated the integration of solar photovoltaic modules with heat pumps, highlighting the efficiency and environmental benefits of such systems in building decarbonization. In addition, Ben Bacha *et al.* (2024) studied the utilization of heat pipes in solar desalination, showing the technology's capability to enhance the performance of desalination systems which is necessary for regions with water scarcity. Additionally, Taner & Dalkilic (2019) conducted a techno-economic analysis of a solar energy plant, revealing the financial viability and sustainability of solar energy investments. These studies collectively show the multifaceted applications of solar energy, from enhancing water pumping systems in agriculture to contributing to the broader context of sustainable development and resource management. Since the main focus of this study is reviewing solar PVWPS in Iran, we stop here and continue a literature review of PV water pumping systems in Iran in the following sections.

## 4. AIM OF THE STUDY

As reviewed, numerous studies have been conducted on solar water pumping systems in various countries, including India (Rathore *et al.* 2018), China (Yu *et al.* 2017), Saudi Arabia (Benghanem *et al.* 2018), Thailand (Imjai *et al.* 2020), and various regions around the world. In the case of Iran, despite its significant solar irradiation potential, there has been limited research on solar water pumping technology. To the best of the authors' knowledge, there is currently no literature review about solar water pumping in Iran. The objective of this paper is to assess the status of research and application of solar water pumping technology in Iran. It aims to summarize the findings and compare the results of these investigations in accordance with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 11 (sustainable cities and communities), and SDG 13 (climate action), among the 17 established goals (*United Nations Sustainable Development Goals (SDGs), n.d.*). Indeed, this study focuses on Iran's solar water pumping systems due to its unique geographical and climatic conditions, which significantly affect system efficiency. Given the lack of comprehensive studies in this area, it aims to provide a detailed current status review, enriching the local knowledge base and supporting tailored solutions for Iran's needs. This approach sets the foundation for future comparative research, enabling more effective evaluations of Iran's solar water pumping progress against global benchmarks. In the paper, a narrative literature review methodology is employed, as evidenced by the extensive examination of existing literature to evaluate the state of solar water pumping technology in Iran. Initially, the paper discusses Iran's geographical location and its solar energy potential. Subsequently, it reviews solar water pumping research and technologies employed within the country.

## 5. GEOGRAPHICAL LOCATION OF IRAN AND ITS SOLAR ENERGY POTENTIAL

Iran, situated in the southwestern part of Asia, is a vast country with a latitude ranging from 25 to 40° North and a longitude spanning from 44 to 65° East (Moshir Panahi *et al.* 2020). The total land area of Iran encompasses approximately 1,648,000 km$^2$ (Rahimi *et al.* 2013). The climate of major areas of this country is characterized as arid and semi-arid and precipitation is limited to the winter months and is generally minimal, except on the northern flanks of the Alborz mountains, where it varies from 40 to 80 in per year (Dewan & Famouri 1968). On the other hand, Iran is ranked as the second-largest extractor of groundwater, with 56% of this water being used in the agricultural sector for food production as well as trade (Dalin *et al.* 2017). Eventually, Iran will be on the brink of a severe water crisis in the years ahead mainly due to the rise in evapotranspiration rates that are attributed to climate change and global warming (Barati *et al.* 2023). For instance, the water reserves in the southwestern part of Iran have an annual evaporation rate of approximately 5,000 mm/year (Bazzi *et al.* 2021).

Table 2 and Figure 7 provide an overview of Iran's 31 provinces and its geographical map, respectively. The adoption of PV systems in Iran commenced in 1982 in Fars province, where they were initially used to supply the necessary electricity for a telecommunications site (Zabihi *et al.* 1998). Subsequently, the utilization of solar energy has gained momentum throughout the country. For example, in 1993, Iran's Ministry of Post, Telegraph, and Telephone initiated a production line for solar cells in Tehran (Zabihi *et al.* 1998).

It is noteworthy that the agriculture industry in Iran consumed a substantial amount of fossil fuels in 2016, including at least 2.7 billion L of diesel fuel, 16.25 million L of kerosene, 5.4 million L of fuel oil, and 237 thousand L of gasoline. This extensive fuel consumption resulted in the emission of approximately 12.5 million tons of $CO_2$ gas (Chahartaghi & Nikzad 2021). Iran is blessed with abundant solar irradiation, experiencing more than 300 sunny days annually (Renewable Energy and Energy Efficiency Organization (SATBA) 2022). Alamdari *et al.* (2013) concluded that the central and southern regions of Iran exhibit a more favourable potential for the utilization of solar energy. Figure 8 illustrates the annual average of total radiation on a horizontal surface in Iran.

In addition to the high solar energy potentials of the country, Gorjian *et al.* (2019) summarized the obstacles to the PV industry in Iran into four categories. The first one is technical gaps leading to the production of low-efficiency PV panels. The second one is Iran's dust and dry weather conditions which both lead to the decrease in output power generation. The third one is the existence of weak governance laws like a rapid decline in government-guaranteed purchase rates. They finally declared the lack of a sustainable roadmap like not financing research and development in this sector as the last barrier.

## 6. SOLAR PVWPS IN IRAN

In the first section, we will review the existing research conducted in the country. In the second part, we will summarize these findings to gain a deeper understanding.

### 6.1. Literature review of the current status of PVWPS in Iran

As previously mentioned, there is a scarcity of studies on solar water pumping applications in Iran (Parvaresh Rizi *et al.* 2019). This section aims to provide a chronological overview of all relevant studies pertaining to PVWPSs in Iran.

**Table 2** | Provinces of Iran

| | | |
|---|---|---|
| Tehran | Kermanshah | Yazd |
| Alborz | Ilam | Esfahan |
| Markazi | Lorestan | Semnan |
| Ghazvin | Khuzestan | Mazandaran |
| Gilan | Chahar Mahaal and Bakhtiari | Golestan |
| Ardabil | Kuhgiluya and Buyer Ahmad | North Khorasan |
| Zanjan | Buschehr | Razavi Khorasan |
| East Azarbaijan | Fars | South Khorasan |
| West Azarbaijan | Hormozgan | Ghom |
| Kordestan | Sistan and Baluchestan | |
| Hamedan | Kerman | |

**Figure 7** | Map of Iran with its 31 provinces (Saatsaz & Rezaei 2023).

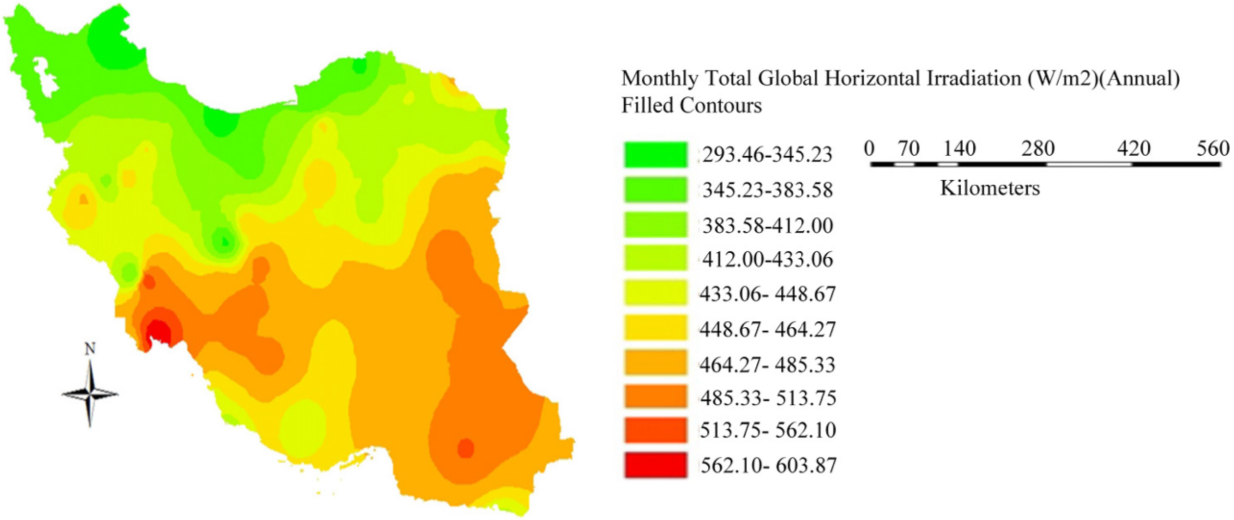

**Figure 8** | Iran's map of annual average of total radiation on a horizontal surface (reproduced from Alamdari Nematollahi & Alemrajabi (2013)).

In 2006, Abdolzadeh *et al.* (2011) evaluated the effect of water spray on the panel's front side on its performance. The experimental setup, located in Kerman, consisted of three and two PV modules each with a nominal power of 45 W, one positive displacement water pump, a controller, a pyranometer, temperature sensors, and flow meters (Figure 9). Three different

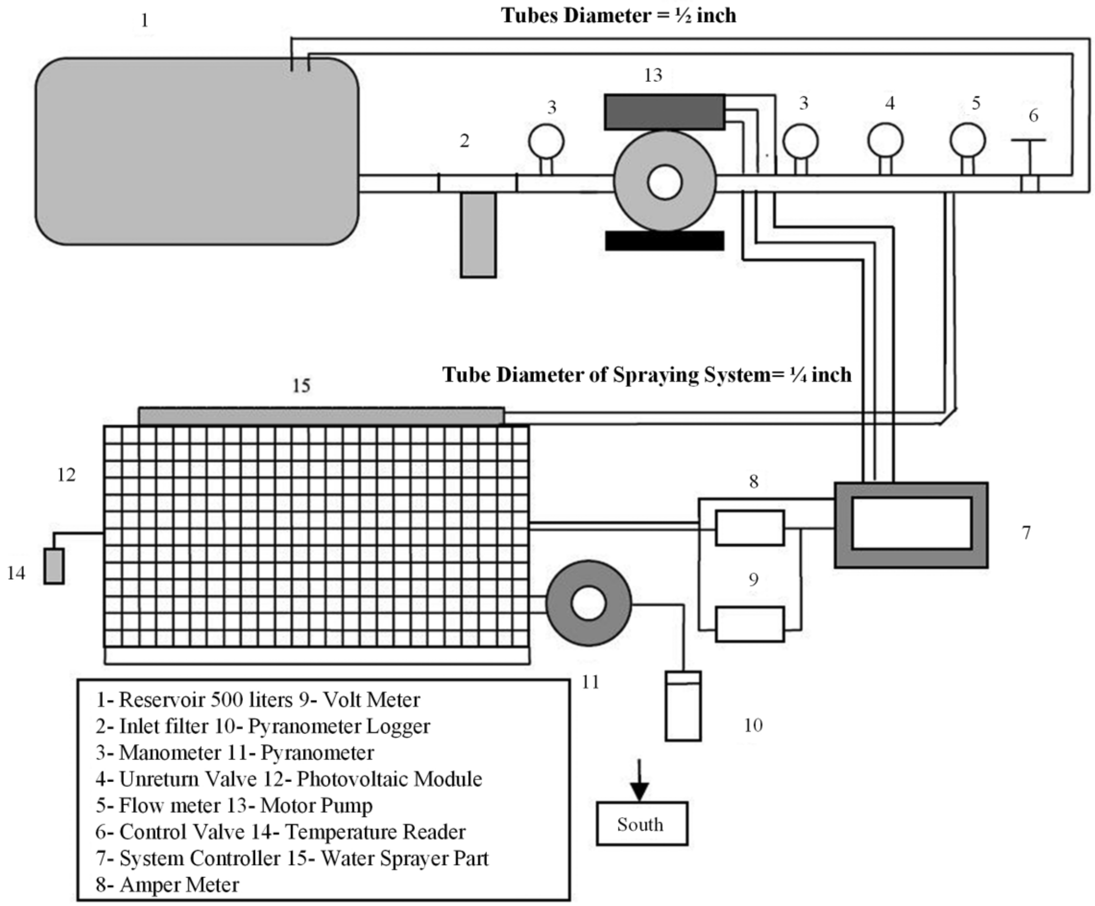

**Figure 9** | Schematic of the experimental setup for reference (Abdolzadeh Ameri & Mehrabian 2011).

cases were considered. In case A, two PV panels were connected with a water spray flow rate of 25 L/h per module. In case B1, three modules were connected with a water spray flow rate of 5 L/h per module. Finally, in case B2, three panels were connected with a water flow rate of 25 L/h per module. In all cases, a total head of 16 m was applied for water pumping. The results of improvements in the performance of the panels and the system are shown in Table 3. It can be seen that in case A, the water pumping of the system increases by approximately 34.4% (from 479 to 644 L/h), while around 40% increment is seen in case of B2 where 25 L/h of cooling water is used per module (i.e., from 600 to 840 L/h). Furthermore, the module efficiency increases from 9.26 to 12.35% in case A, and from 8 to 10.16% and 12.35% in cases B1 and B2, respectively,

**Table 3** | Details of the cooling effect on the performance of the system (Abdolzadeh *et al.* 2011)

| Parameters | Two PV modules | | Three PV modules | | |
|---|---|---|---|---|---|
| Case | No cooling | Water spray (A) | No cooling | Water spray (B1, B2) | |
| PV output power (W) | 55.4 | 66.9 | 71.39 | 84.8 | 97 |
| Pumping flow rate (L/h) | 479 | 644 | 600 | 744 | 840 |
| PV module efficiency (%) | 9.26 | 12.35 | 8 | 10.16 | 12.35 |
| Global irradiation (W/m$^2$) | 800 | 800 | 800 | 800 | 800 |
| Total Efficiency (%) | 3.75 | 5.1 | 3.69 | 4.4 | 5.11 |
| Water spray (L/h) | – | 50 | – | 15 | 75 |

which are considerable improvements due to the hot weather conditions of Kerman City. The same authors (Abdolzadeh Ameri & Mehrabian 2009) evaluated the impact of operating head on PVWPS performance with the same setup shown in Figure 9 in Kerman. The research investigated two different configurations (two and three panels each 45 W connected in parallel) and four different operating heads (6, 10, 16, and 20 m) in order to increase the efficiency of the system. Their investigation focused on the importance of selecting the maximum power corresponding to the chosen head and meeting the requirements of the user to reduce installation costs. Different parameters affecting PVWPS efficiency, including array arrangement, and pump flow rates, were evaluated. It was shown that the maximum array efficiency is observed at a head of 20 m for a three-panel configuration, reaching an efficiency of approximately 10%. However, the efficiency decreases at lower heads due to a mismatch between PV and motor-pump power. The results highlight the significance of considering both the power of the pump at maximum speed and consumer needs in PVWPS design to minimize the capital costs of the project.

Kordzadeh (2010) studied the efficiency of PV panels employed in water pumping applications. The primary objective of this investigation was to identify methods for enhancing the conversion rate of the panels and the water pumping system. The research involved the installation of PV panels in Kerman, a city known for its high solar irradiation potentials. As the operating temperature of PV cells increases, their open-circuit voltage diminishes, subsequently affecting their efficiency and output power. Thus, the study aimed to explore the impact of system head and nominal array power on the efficiency of water pumping systems. To mitigate the temperature rise of the panels, a thin layer of water was circulated over their surface. The experimental system consisted of three panels, a controller, a motor-pump with the model of PS150 Boost Lorentz, and a filter (refer to Figure 10). The maximum pump head was 45 m, with a maximum mass flow rate of 1,000 L/h. The pump's role was to supply a thin film of water to the panels. Irradiance levels were monitored using a pyranometer. Two sets of PV panels with nominal powers of 90 and 135 W were employed (two or three panels each with a nominal power of 45 W), along with three different system heads of 10, 12.5, and 16 m. The study revealed that the application of a thin water layer on the panels could enhance the optical characteristics of PV cells, leading to an increase in the short-circuit current, which is temperature dependent. Consequently, this improvement resulted in an increase in the overall output power. The study's conclusion emphasized that a reduction in nominal array power and an increase in the system head could lead to enhanced power generation and improved overall system efficiency. As evident in Figure 11, the efficiency of the panel is in the range of about 7–14% for different conditions.

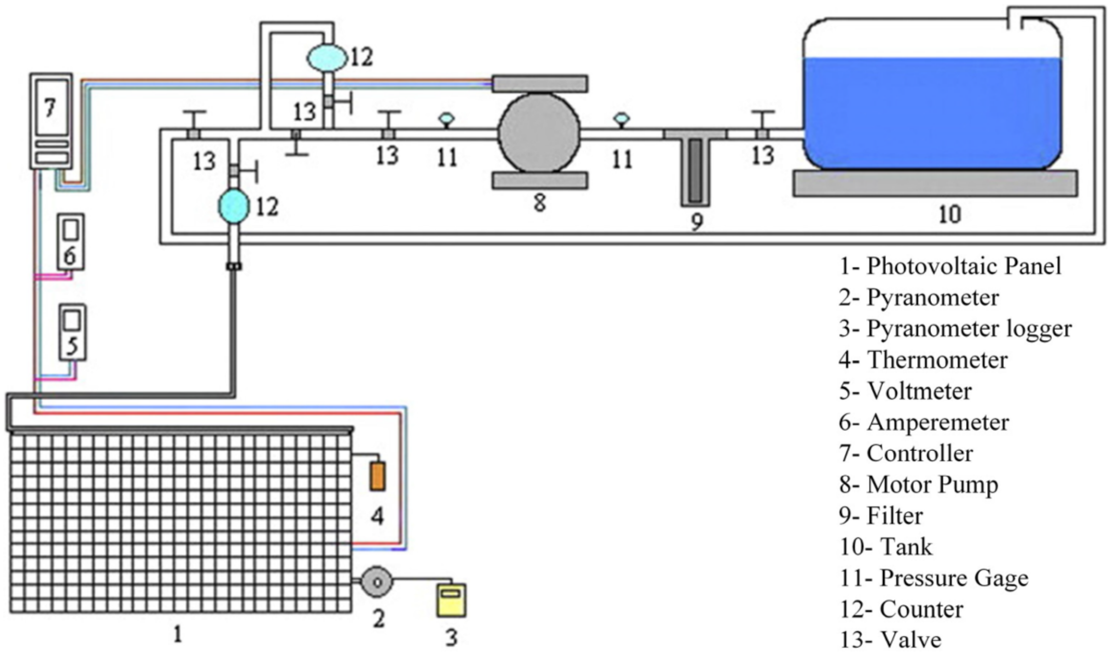

**Figure 10** | Schematic of the experimental setup used in Kordzadeh (2010).

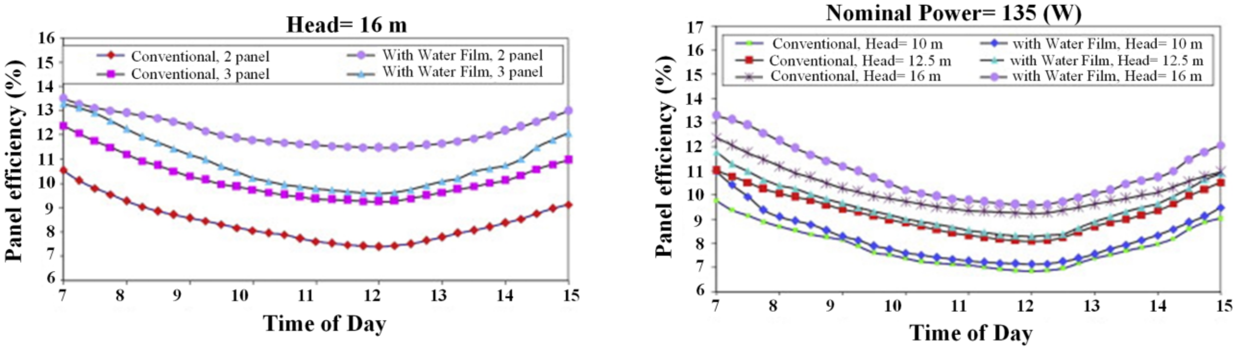

**Figure 11** | Impacts of PV nominal power (left) and head (right) on panel efficiency (Kordzadeh 2010).

Tabaei & Ameri (2012) conducted a study to evaluate the impact of booster reflectors on the efficiency of a solar water pumping system at Shahid Bahonar University of Kerman in the city of Kerman during the summer season. The study examined two different materials for these reflectors: stainless steel 304 and aluminium foil, with the goal of assessing their effects on power generation and water pumping flow rates. The PV panels were tilted to the latitude of Kerman city, which is approximately 30°. To enhance energy extraction, an MPPT system was employed. The study revealed that aluminium foil reflectors outperformed stainless steel in terms of both power generation and water pumping flow rates. This superiority was attributed to the higher reflectivity characteristics of aluminium compared to stainless steel. The use of reflector boosters was found to have two opposing effects on the system's performance. On the one hand, it increased irradiation values, which, in turn, raised the output current of the panels. On the other hand, it led to an enhancement in panel temperature, which is unfavourable as it reduces the panel voltage. However, the study demonstrated that the positive impact of the current increment outweighed the negative effect of voltage reduction. Consequently, the use of a reflector booster was deemed beneficial for the system. The study did not employ any cooling technique to keep the panel temperature low but suggested using passive or active cooling methods to improve the performance of PV panels with concentrators. The study indicated that the daily average power generation saw an increase of 14% with aluminium foil reflectors and 8.4% with stainless-steel foil reflectors. Furthermore, an 18% increase in pump flow rates with the aluminium foil reflector and a 9% increase for the stainless-steel reflector were reported. Figure 12 shows a comparison of conventional panels without reflectors (WRs) with panels with aluminium foil reflectors (WAFRs) and panels with stainless-steel reflectors (WSSRs) in terms of output power and pumped water flow rates.

Rezae & Gholamian (2013) conducted a study relevant to solar water pumping in the north of Iran. They employed RETScreen software to analyse the technical and financial aspects of solar water pumping systems. The study focused on water pumping for a farm field located in Gorgan city, the administrative centre of Golestan province with a latitude of 36.8° North and a longitude of 54.5° West. The study reported the average solar irradiation in this city as 4.35 kWh/m$^2$/day, with a maximum of 6.42 kWh/m$^2$/day in June and a minimum of 2.2 kWh/m$^2$/day in December. Their investigation involved a PV panel (SANYO HIT Power 195 BA20) with two diodes. The model comprised a PV array, a power conditioner, a battery bank (ATLAS BX; 12 V-100 Ah), and a pumping system (MOTOGEN-CR90L2A electromotor) designed to meet the water demands of the farm during the irrigation time, which spans from April to September. The battery storage is used to provide energy at night for water pumping. Regarding financial analysis, the study compared the income generated by the renewable energy system with that of a conventional diesel pumping system. The project's expected lifetime was set at 25 years, with an inflation rate of 10%. Initially, the study considered the price of government-subsidized gasoil. The research demonstrated that the payback period for the renewable project was 14 years under these conditions. However, when considering the price of gasoil at the FOB Persian Gulf market, the payback period is reduced to 6 years (Figure 13). The study concluded that the adoption of solar energy could be further incentivized by government-provided loans for renewable energy projects. Furthermore, fixed efficiency for motor-pump systems is used which can lead to substantial errors in numerical simulations.

In 2015, Habiballahi *et al.* conducted a study aimed at improving the efficiency of PV panels through water cooling (Habiballahi *et al.* 2015). The primary objective of the study was to enhance the efficiency of PV panels and consequently

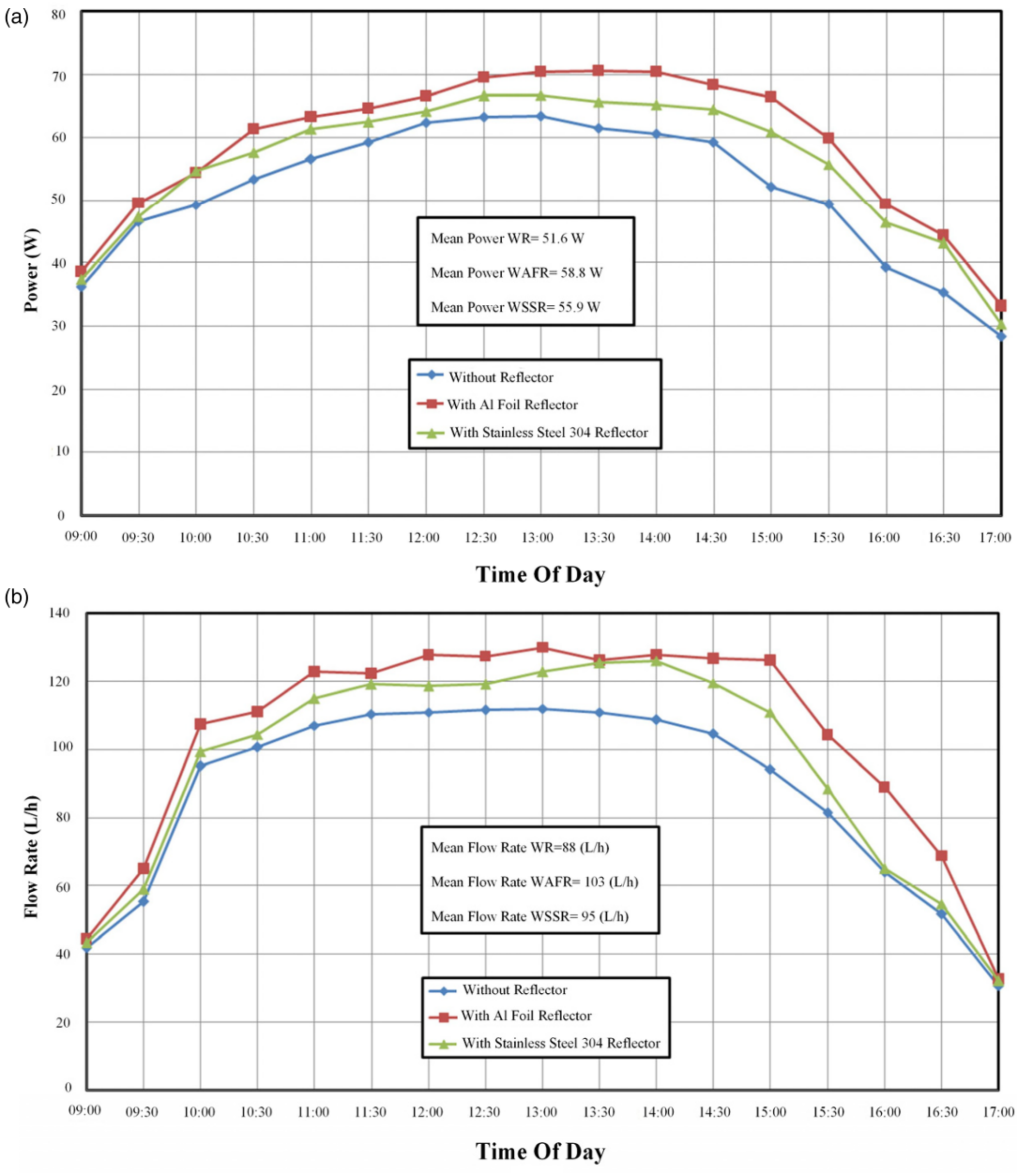

**Figure 12** | Comparison of (a) power and (b) flow rate improvements for different reflectors (Tabaei & Ameri 2012).

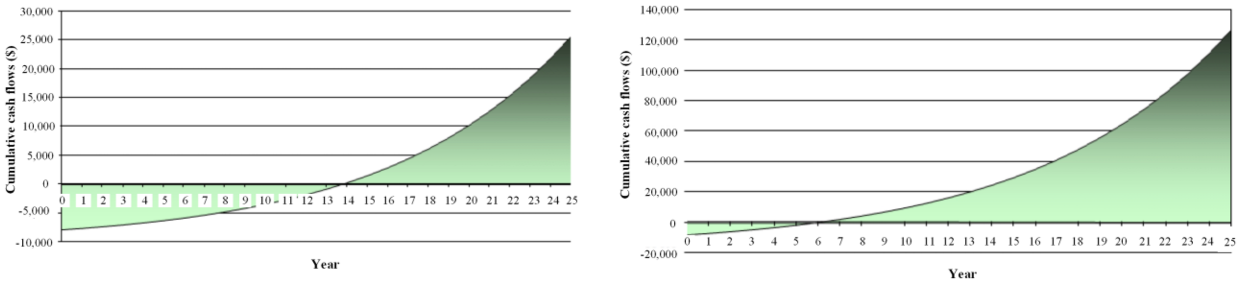

**Figure 13** | Cumulative cash flow for subsidized gasoil price (left) and Persian Gulf market gasoil price (right).

the water flow rate by implementing thermal collectors positioned beneath the PV surface. The pumping mechanism directs water through these collectors, where it serves to cool the system before being redirected into the primary water pumping path. The experimental setup, located in Kerman, consisted of three 45 W PV modules connected in series, one positive displacement water pump featuring a DC motor (PS150 Boost with 45 m maximum head and maximum flow rate of 850 L/h), a controller, a pyranometer for measuring solar irradiance, three temperature sensors, and two flow meters, as depicted in Figure 14. The PV panels were tilted at an angle of 30°, matching the latitude of Kerman city. The study considered two different heads of 10 and 16 m, along with three distinct collector mass flow rates. The results of the study revealed that at a head of 16 m and a collector mass flow rate of 310 L/h, the PV cell efficiency and the overall efficiency of the PVWPS increased by 2.04 and 1.08%, respectively. This led to about a 20% improvement in mean power and a 29% increase in mean water flow rate.

In another study conducted in 2015 by Tabaei & Ameri (2015), the detrimental impact of increasing cell temperature on the efficiency of PV panels in a solar water pumping system incorporating booster reflectors was investigated. In this study, the panels were effectively cooled by circulating water through the pumping system and providing a continuous film on the panel front surface. Following the cooling process, the water was redirected into the main water pumping stream, eliminating the need for additional water for cooling purposes. The measurements were conducted over a 3-week period in June and July. The optimized angle of the reflectors relative to the horizon was obtained to be 45°, as shown in Figure 15. The position of the PV panels and the reflectors are illustrated in Figure 16. The study examined four different conditions for the PV panels: (1) without a reflector, (2) with a reflector, (3) without a reflector and with a water film, and (4) with a reflector and with a water film. The findings of the study indicated that panels equipped with booster reflectors and cooled with a water film demonstrated the best performance among the tested configurations. Specifically, panels with reflectors and a water film improved the panel's output power by up to 50.4%. For comparison, details are given in Table 4.

Mohammadi (2015) conducted a numerical analysis to optimize the technical and economic aspects of a solar water pumping system. While the exact location of the study was not specified, it was mentioned that the study focused on the southern part of Iran with the goal of providing 56 $m^3$ of water per day for irrigation and drinking. An analogy between battery bank and water tank was applied in the simulation. Two key parameters, LLP and life cycle cost, were considered to evaluate the performance of the water pumping system. The LLP was defined as the ratio of water deficit to water demand. These two parameters exhibited a conflicting relationship: increasing the number of panels improved technical reliability but reduced economic viability. Figure 17 depicts the Pareto front solution of cost versus LLP at a pumping head of 14 m. To address

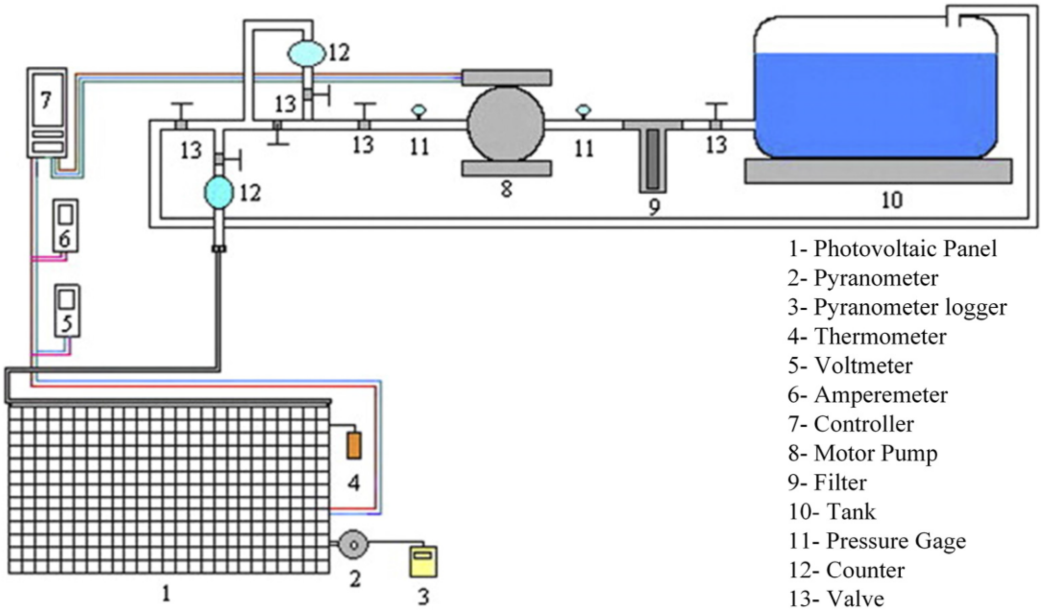

**Figure 14** | Schematic of the experimental setup used in Habiballahi Ameri & Mansouri (2015).

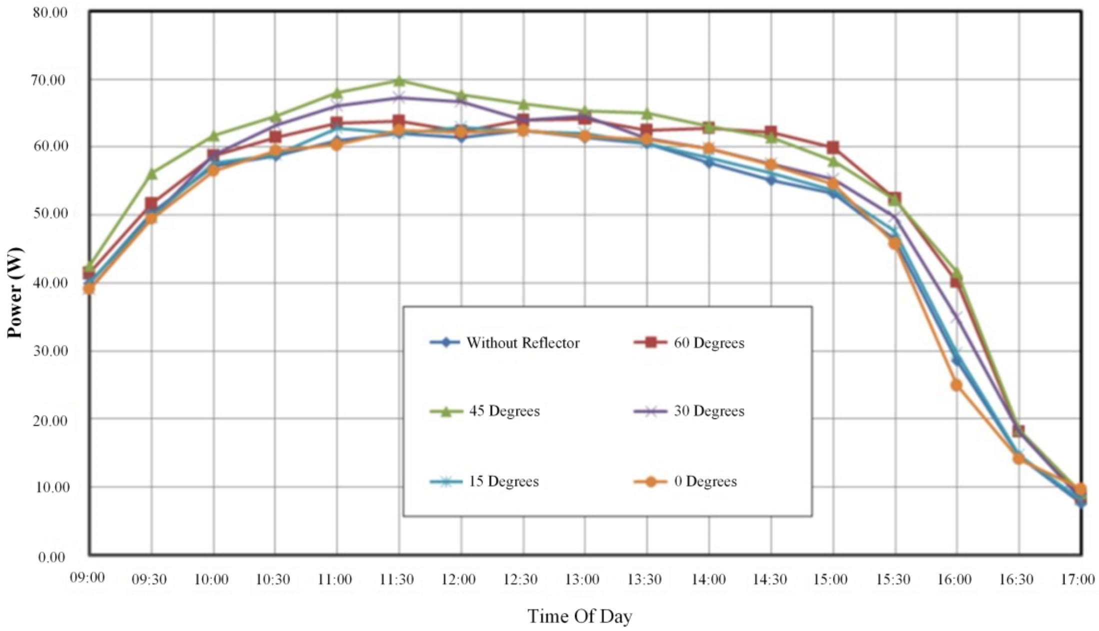

**Figure 15** | Variations of output power at different reflector positions (Tabaei & Ameri 2015).

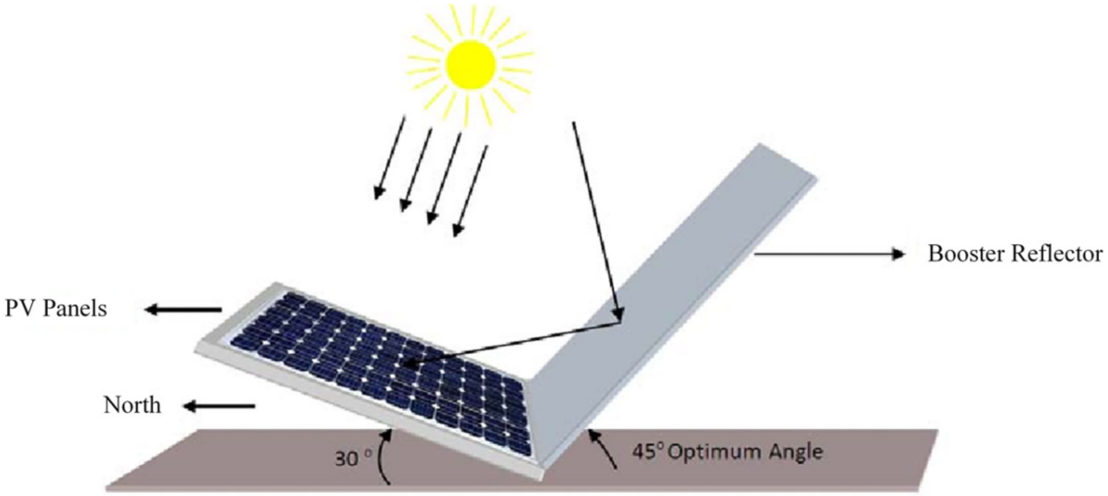

**Figure 16** | Position of PV panels and the booster reflector with respect to the horizontal plane (Tabaei & Ameri 2015).

**Table 4** | Improvements in output power by using reflector and water cooling (Tabaei & Ameri 2015)

| | **Conventional panels** | **Panels with reflector** | **Panels with cooling** | **Panels with reflector and cooling** |
|---|---|---|---|---|
| Mean daily power (W) | 51.6 | 58.8 | 60.8 | 77.6 |
| Improvement (%) | Not applicable | 14.0 | 17.8 | 50.4 |

this complex problem, the non-dominated sorting genetic algorithm method was employed, yielding various decision variables for the obtained solutions. The number of PV panels was changed from 2 to 5 each with 55 W of nominal power while autonomy days for the water tank varied from 3 to 9 days.

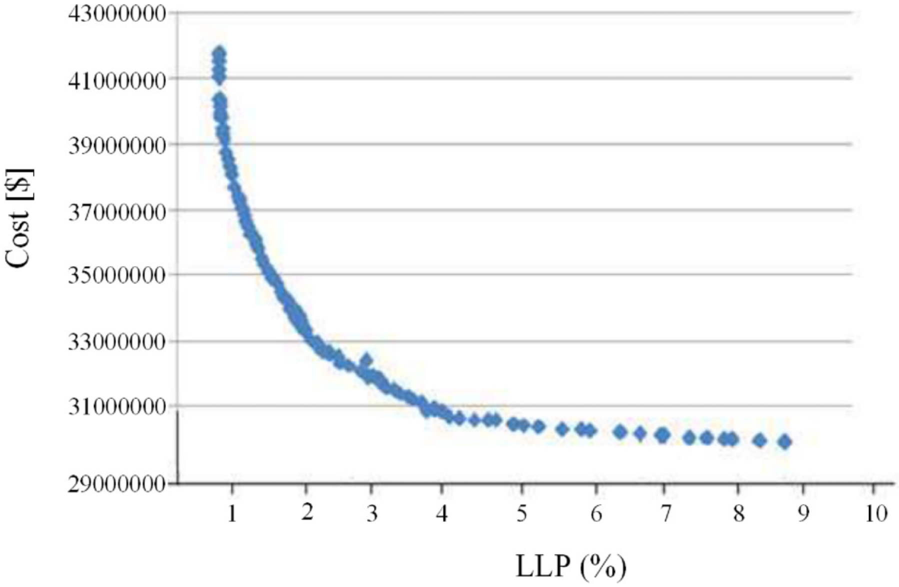

**Figure 17** | Pareto front solution for a constant pumping head of 14 m (Mohammadi 2015).

In the same year, Karami Rad *et al.* (2015) carried out a feasibility study in which they designed a standalone solar-based Microner sprayer, creating a prototype for technical evaluations (Figure 18). A small battery was employed to serve as a stabilizer in the system. The system consisted of a sprayer, a 10-W solar power supply, and a control system. Meteorological data from NASA (The National Aeronautics and Space Administration (NASA) n.d.) for Karaj in the Alborz province were used in the study, with LabVIEW software employed for data acquisition. The system was capable of operating for 7–9 h/day which makes it an applicable system for use in agriculture spraying. The study demonstrated that this designed system could be deployed in remote areas to address environmental challenges and the lack of access to traditional fossil fuel systems.

**Figure 18** | SKN-3000 sprayer setup used in reference (Karami Rad *et al.* 2015).

Niajalili *et al.* (2017) conducted an investigation into solar water pumping in the north of Iran, specifically in Gilan province. The location of the study is shown in Figure 19. This region experiences significant average precipitation levels. It is worth noting that the cuisine in Iran is known for its diversity, but rice-based dishes are staples for the majority of the population (Karizaki 2016). Rice is a primary agricultural product in the northern part of the country. Given this, the use of a solar water pumping system for rice cultivation in the northern regions becomes particularly interesting. The study of Niajalili *et al.* (2017) encompassed both technical and economic aspects of employing solar water pumping for rice fields. The technical analysis involved determining the sizing requirements for PV panels, while the economic study included assessing the life-cycle costs and comparing them to conventional pumping systems. One of the main challenges highlighted in the paper was the high initial cost associated with solar systems. However, the decreasing price of PV panels and the instability of fuel prices were cited as compelling reasons for the growing interest in PV systems. Due to the relatively lower solar irradiation levels in Gilan province compared to other regions, the study considered only the sunny months of the year. During the summer, the average daily temperature in the region is around 25 °C, with a minimum relative humidity of 74%. On average, there are 5.81 h of sunshine per day during the summer, making it suitable for irrigation purposes. The

**Figure 19** | Location of Gilan Province in northern Iran (Niajalili *et al.* 2017).

study focused on a rice field with an area of 5,000 m$^2$, using irrigation water requirements (IWRs) as the basis for determining water demand for the rice paddies. While there are many cloudy days, the average clearness index during the irrigation period justified the use of PV pumping systems in Gilan province. To account for cloudy days, the model included batteries to ensure continuous operation. To compare the PV system with conventional non-renewable water pumping systems, the study examined a gasoline-driven pump for supplying water to the rice paddy. The schematic of both PV and gasoline-based pumping systems is shown in Figure 20. The economic analysis revealed that the initial cost of the PV solar pumping system was seven times higher than that of the conventional gasoline motor-pumping system. However, it took approximately 9 years for the total cost of both systems to equalize, after which the renewable system became more cost-effective than the gasoline system. Over a 25-year period of irrigation, the final expenses of the gasoline system were about 1.56 times that of the PV pumping system, demonstrating the cost-efficiency of the renewable system in the long term. Figure 21 illustrates the life cycle cost of the system.

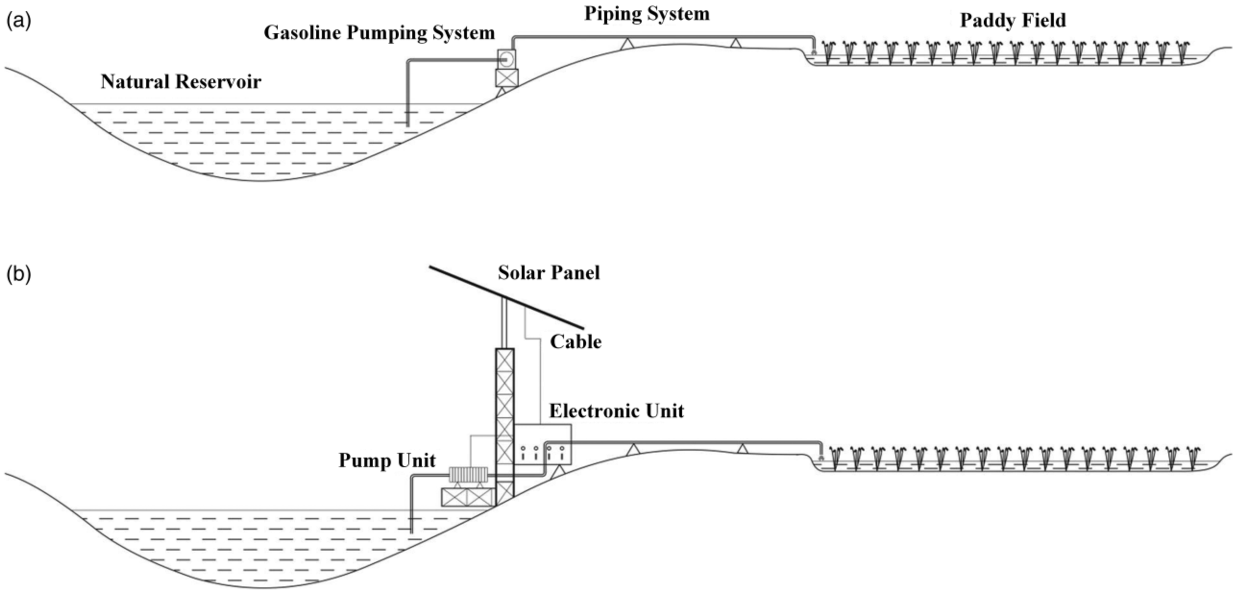

**Figure 20** | Schematic of (a) gasoline pumping system and (b) PVWPS (Niajalili *et al.* 2017).

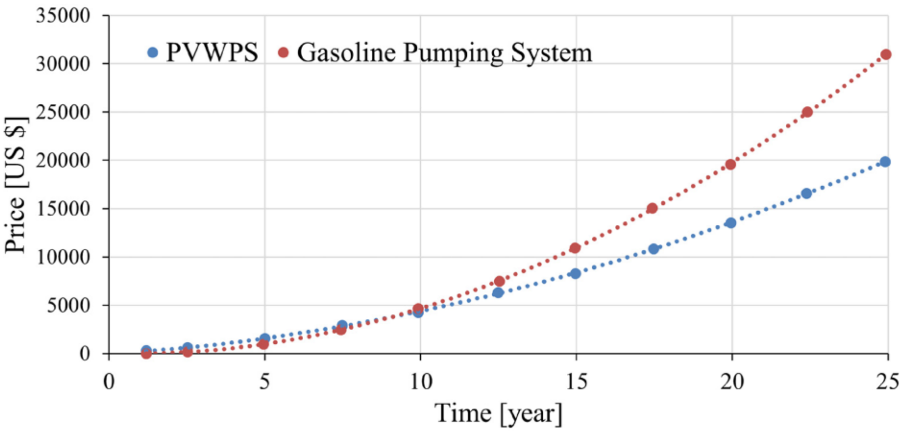

**Figure 21** | Lifecycle cost estimation over 25 years (reproduced from Niajalili *et al.* (2017)).

In 2018, Shirinabadi *et al.* (n.d.) evaluated the feasibility of solar PV systems for a water pumping station in Tabriz, northwest of Iran, aiming to reduce national grid use and to decrease the environmental impacts. They studied an 800 kW PV power plant equipped with a two-axis sun tracker. They used PVSYST software to simulate the performance of the system while taking into account parameters including losses and geographic location. The annual global horizontal irradiation of the location was 1,886.4 kWh/m$^2$ and the global panels' incident irradiation of 2,169.1 kWh/m$^2$. They used 2670 PV panels each with nominal power of 300 W to produce the required electricity for running four AC horizontal centrifugal electro-pumps each with a capacity of 250 kW. The system comprised of 92 inverters of 8.6 kW nominal power with 96.5% efficiency. The goal of the study was to investigate the feasibility of replacing a conventional grid-based water pumping system with PVWPS. They concluded that the proposed system could avoid the emission of approximately 509 tons of $CO_2$-eq per year. In a 2019 study by Parvaresh Rizi *et al.* (2019), two case studies were analysed, focusing on a citrus orchard in the southern city of Jahrom and a vineyard in the eastern city of Kashmar, both located in Iran. The research aimed to assess the financial aspects of solar water pumping systems in comparison to conventional irrigation pumps powered by either grid electricity or fossil fuels. This analysis encompassed three types of pumps: solar, diesel, and electricity-driven pumps. The schematic of the model used for the study is depicted in Figure 22. The researchers' findings revealed several key points. For pumps with power ratings exceeding 3 kW, it was generally more economically viable to obtain the required electricity from a private power line than to generate electricity locally using a solar PV system. This was especially true if the transmission line was located within 2 km of the site. However, for pumps with power ratings below 4.5 kW, a solar water pumping system was found to be competitive with fossil fuel-based systems. The study noted that Iran heavily subsidizes fossil fuels, resulting in low fuel and electricity costs. As a consequence, investment in solar pumping systems faces financial challenges and may only become feasible with the introduction of new policies and incentives. Furthermore, the research highlighted that the relatively high-interest rates set by banks for investments in Iran make renewable energy less financially attractive. Another factor impacting the adoption of solar systems in Iran is the dependency on imported solar pumping components. The prices of these components are primarily influenced by the exchange rate between the US Dollar and the Iranian Rial. This exchange rate is subject to significant fluctuations, often linked to Iran's foreign policy decisions, and can negatively affect the affordability and feasibility of solar systems for individuals and business owners. In summary, while solar water pumping systems hold potential benefits for irrigation in Iran, various economic and policy-related challenges, such as fuel subsidies, interest rates, and exchange rate fluctuations, need to be addressed to promote their widespread adoption. The parameters affecting the energy source selection for irrigation pumping are shown in Table 5.

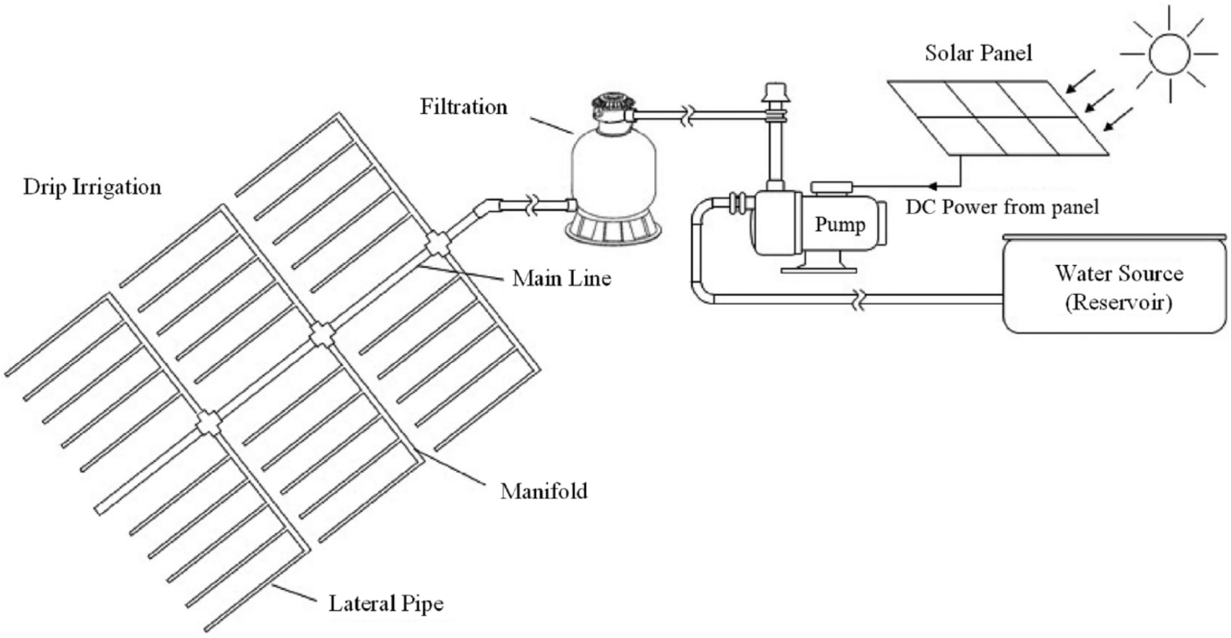

**Figure 22** | Schematic of the design model of study reference (Parvaresh Rizi Ashrafzadeh & Ramezani 2019).

**Table 5** | Importance of affecting factors for energy source selection for irrigation pumping (Parvaresh Rizi *et al.* 2019)

| Energy source for irrigation pumps | Priority of financial constraints | Importance level |
|---|---|---|
| Electricity | Distance from the grid | High |
| | Availability of pumps and other instruments | Moderate |
| | Cost of electricity per year | Low |
| Diesel | Availability of pumps and other instruments | Moderate |
| | Fuel supply and its cost in the operation period | Low |
| Solar | Preparation of equipment for solar power generation | High |
| | Preparation of equipment for power generation efficiency improvements | High |
| | Availability of pumps and other instruments | Moderate |

In 2019, a research study was conducted at the Gharakhil Weather Station in Mazandaran province, located at a latitude of 36° North and a longitude of 52° East (Chahartaghi *et al.* 2019). This study focused on solar water pumping and involved mathematical modelling. The researchers aimed to understand how the tilt angle of solar panels affected the water pump's discharge throughout the year. Additionally, the study explored how ambient temperature influenced the efficiency of the water pump. The novelty of the research was in the utilization of a solar pumping system for running a drip irrigation network. The solar water pumping system in this investigation was designed for direct coupling with drip irrigation, and notably, it did not incorporate a battery bank. The findings indicated that the system achieved its maximum annual water discharge when the solar panels were tilted at angles close to the latitude (i.e., at a tilt angle of 41°) (Figure 23). Moreover, the study highlighted that an increase in the panel temperature could significantly diminish their power generation capacity, particularly during the hot season due to an approximate 11% reduction in PV panel efficiency.

In another 2019 study, Zamanlou & Iqbal (2019) conducted a feasibility analysis of a solar water pumping system in Urmia City, West Azarbaijan, located in northwest Iran. Their study focused on a grape garden spanning an area of 2.36 ha and 9,638 $m^3$ of water requirement for irrigation per year. This amount of water should be pumped to an elevation of around 25 m with a friction loss of 2.15 m. Based on the average sunshine hours of the region which equals 8.8 h/day, they selected a volumetric flow rate of 6 $m^3/h$ for the garden irrigation. The system was equipped with battery banks and MPPT in order to maximize irradiation harvest. To determine the irrigation water requirements, they employed the CropWat model. The selection and sizing of electrical components for the system were carried out using HOMER Pro software. The researchers used

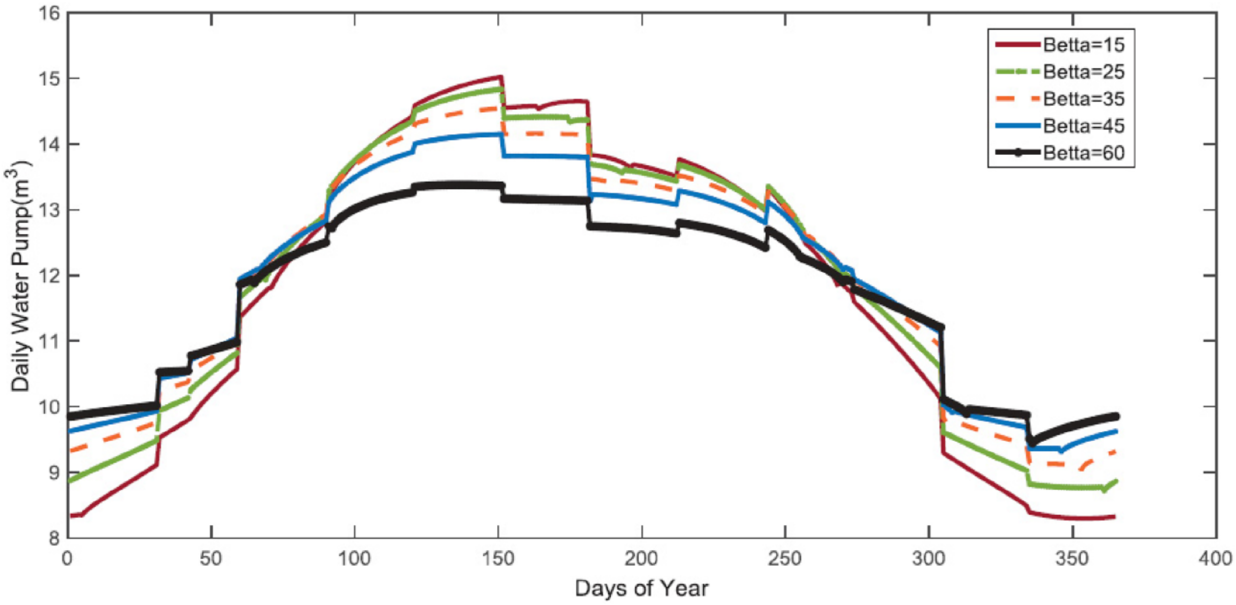

**Figure 23** | Volume of pumped water at different tilt angles (Chahartaghi Mehdi & Jaloodar 2019).

the Lorentz Compass program to choose an appropriate water pump, and MATLAB Simulink was utilized for assessing the dynamic performance of the system in terms of electricity generation and load requirements. Despite the feasibility study and from an economic perspective, they estimated the total cost of the irrigation system to be approximately 24,000 CAD. They also showed that the MPPT system was successfully operating and its voltage at maximum point tracking was very close to the PV voltage at laboratory conditions of 25 °C and 800 $W/m^2$ irradiance.

In 2019, a case study on solar water pumping was conducted in the city of Sari, located in Mazandaran province in northern Iran, with coordinates at approximately 36.57° North latitude and 53.06° East longitude (Nikzad *et al.* 2019). This study included a notable comparison of solar irradiation levels in Mazandaran province with those in Germany. The research revealed that the average solar irradiation in this region ranged from 3.8 to 4.2 $kWh/m^2/day$, which exceeded the average of 3.3 $kWh/m^2/day$ observed in Germany. It's worth noting that other regions in Iran generally receive higher solar irradiation levels compared to the northern parts. The study encompassed a comprehensive analysis of economic, environmental, and technical aspects related to a 1-ha (10,000 $m^2$) rice paddy. One novel aspect of this research was the consideration of electricity generation during non-irrigation months, with the excess electricity being sold to the government under a 20-year power purchase agreement (PPA) established by the Iranian Ministry of Energy. This PPA guaranteed government procurement of the generated electricity. However, it was essential for the land to be situated in proximity to a power grid. From an environmental perspective, the study highlighted reductions in $CO_2$ emissions, noise pollution, and savings in natural gas, oil, and fuel. Regarding the technical aspects of the system, the researchers explored factors such as the optimal tilt angle for solar panels, the sizing and arrangement of PV panels, and the design of a battery backup system. A VICTRON Energy MPPT charge controller is used in the system. During the study, a growing period of 145 days was considered for rice cultivation, spanning from April 15 to September 6. Additionally, the research accounted for 15 cloudy days, with a maximum of three consecutive cloudy days occurring in each month. For the economic analysis, two scenarios were investigated: an off-grid model and an on-grid model. In the on-grid model, surplus power could be sold to the government under a predetermined agreement. The findings indicated that the capital cost of the on-grid model was 2.41 times that of the conventional diesel pumping system, as illustrated in Figure 24. However, over a 20-year operational period, the life cycle cost of the conventional system would be 2.89 times that of the on-grid model. The payback period for the on-grid model was estimated to be approximately 4.7 years. On the other hand, the capital cost of the off-grid model was 2.14 times that of the conventional diesel pumping system. Nevertheless, after 20 years of operation, the life cycle cost of the conventional diesel system would be only 1.30 times that of the off-grid renewable model. The payback period for the off-grid model was estimated to be 5.6 years. Furthermore, it was concluded that transitioning from the conventional pumping system to the off-grid solar system could prevent the release of about 5 tons of $CO_2$. Additionally, this transition would lead to reduced consumption of

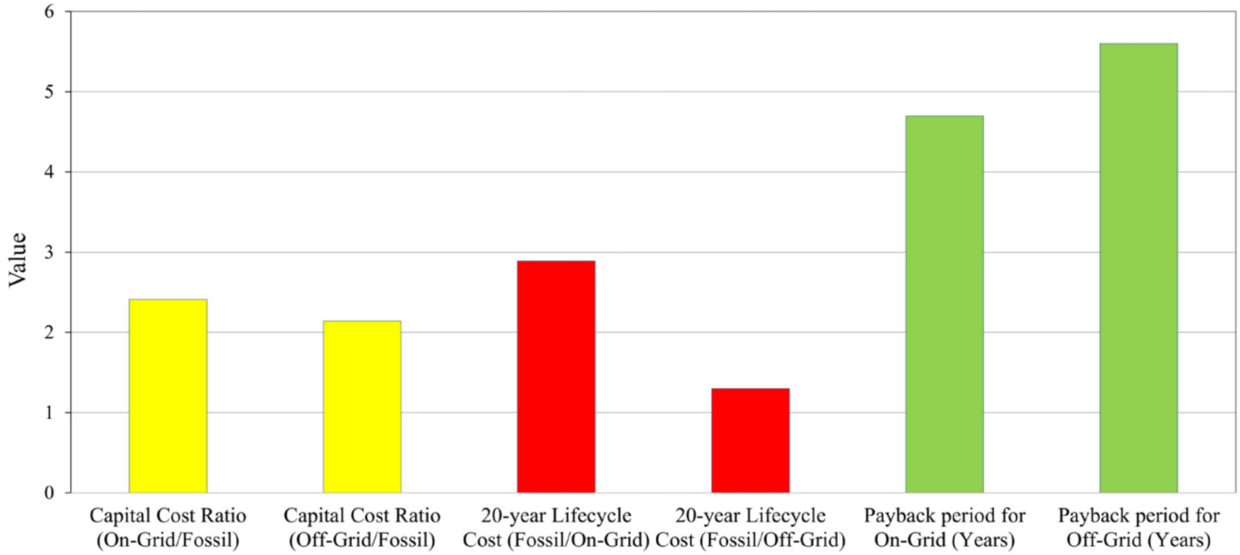

**Figure 24** | Financial comparison of different models for reference (Nikzad Chahartaghi & Ahmadi 2019).

diesel fuel and engine oil by approximately 1,750 and 85 L, respectively. In terms of noise pollution, the on-grid solar water pumping system emitted 71% less noise compared to the conventional diesel motor-pump system. The noise produced by the diesel engine was experimentally measured by Sound Meter Smart Tools software installed on a Samsung cell phone. It's important to note that the off-grid model did not contribute to noise pollution.

In a study conducted by Shayeteh & Kardehi Moghaddam (2020), a multi-objective firefly algorithm based on crowding distance (CD-MOFA) was employed to optimize a PV water pumping station located in Bojnurd, northeast of Iran. This battery-less system comprised PV arrays, inverters, an AC motor-pump system, and a storage reservoir. The system is designed to pump water to a hydraulic head of 84 m. The climate data specific to the station were obtained from Meteonorm software, and MATLAB was employed for numerical simulations. The non-optimized system was introduced as an existing system with 25 PV arrays with a total power capacity of 3.96 kW tilted at 39° with an azimuth angle of −5 that could produce 76 $m^3$ of water per day. The optimization process focused on two key variables: the solar azimuth angle and the tilt angle. By optimizing these variables, the researchers aimed to increase the water pumping capacity of the system while simultaneously minimizing its overall cost. In fact, they considered two conflicting objective functions: annual revenue and life cycle cost of the system. The developed algorithm optimizes the yearly income by making a balance among annual revenue, initial expenditures, operational and maintenance, and replacement costs. This results in an increase in the water output and consequently maximizes profits from water sales. Furthermore, it minimizes the system size, hence lowering overall costs. Five different configurations of the optimized system were evaluated, as shown in Table 6. Their findings demonstrated that the utilization of this optimization method led to a notable reduction in the system's cost and payback period, achieving a reduction of approximately 19% compared to a system with no optimization.

In another study conducted by Ghasemi-Mobtaker *et al.* (2020), a 100-ha barley farm located in Hamedan was subjected to numerical analysis for two distinct irrigation scenarios: surface irrigation (SFI) and sprinkler irrigation (SPI) by using grid electricity and fossil fuel. The study also aimed to evaluate the potential of utilizing a PV system as an alternative technique for irrigation and barley cultivation in comparison to conventional methods named SFI-PV and SPI-PV. To conduct this analysis, the researchers employed TRNSYS software for numerical simulations, while climate data specific to the location were sourced from Meteonorm software. The focus of the study was on assessing the energy consumption and environmental impact of each irrigation scenario. The contribution of each energy source for two techniques of SFI and SPI is shown in Table 7 and depicted in Figure 25 for energy inputs. For energy inputs, it can be seen that for SFI, electricity has the main contribution (around 50%) while diesel fuel has the main share for the SPI method (around 40%). To evaluate energy indices of barley production and based on the definition of energy use efficiency (EUE), which is total output energy (TOE) divided by total input energy (TIE), they showed that EUE for SPI and SFI techniques are 2.8 and 2.85, respectively. Energy equivalent values for the diesel fuel used in both irrigation techniques are calculated and added to the electricity energy used and the total amount that should be replaced by solar PV panels are obtained as 1,959 and 2,285 kWh for SFI and SPI, respectively. The TRNSYS simulations for irrigation for the production period of barley cultivation showed that the maximum PV power for SFI-PV and SPI-PV systems are 4.55 and 5.20 kW, respectively. Furthermore, the results of the study revealed that, given that pumping stations typically rely on diesel fuel for pumping operations, the sprinkler irrigation method resulted in substantial $CO_2$ emissions equal to 1,184 kg/ha compared to 425 kg/ha for SFI. On the other hand, it was demonstrated that, from an

**Table 6** | Comparison of different configurations of study (Shayeteh & Kardehi Moghaddam 2020)

| Parameter | Not optimized | Optimized system 1 | Optimized system 2 | Optimized system 3 | Optimized system 4 | Optimized system 5 |
|---|---|---|---|---|---|---|
| Total cost (Rial*$10^6$) | 212.34 | 212.34 | 203.84 | 195.35 | 186.86 | 178.36 |
| Annual profit (Rial*$10^6$) | 74.49 | 93.30 | 89.67 | 85.31 | 81.42 | 78.55 |
| PV number (–) | 25 | 25 | 24 | 23 | 22 | 21 |
| Capacity (W) | 3.96 | 3.96 | 3.84 | 3.68 | 3.52 | 3.36 |
| Tilt angle (°) | 39 | 31 | 32 | 30 | 29 | 34 |
| Azimuth angle (°) | – 5 | – 21 | – 19 | – 25 | – 20 | – 26 |
| Pumped water ($m^3$) | 76 | 101 | 94 | 89 | 84 | 79 |

**Table 7** | Details of input and output energy sources for barley production in Hamedan (Ghasemi-Mobtaker *et al.* 2020)

| | | Input (unit) | | | | | | | | | | Output (unit) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | Scenario – | Human labour h | Agricultural machinery kg | Diesel fuel L | Nitrogen fertilizer kg | Phosphate fertilizer kg | Farmyard manure kg | Pesticides kg | Electricity kWh | Seed kg | Total energy use MJ | Barley kg | Straw kg | Total energy output MJ |
| Unit per ha | SFI | 85.8 | 11.56 | 101.2 | 69 | 45.5 | 5,000 | 0.7 | 1,481.76 | 240 | – | 5,300 | 2,500 | – |
| | SPI | 41.1 | 11.91 | 282.2 | 69 | 45.5 | 5,000 | 0.7 | 952.56 | 240 | – | 5,600 | 3,000 | – |
| Energy content (MJ/ha) | SFI | 168.17 | 1,649.61 | 5,698.57 | 4,563.66 | 566.02 | 1,500 | 139.30 | 17,677.4 | 3,528 | 35,490.73 | 77,910 | 23,150 | 101,060 |
| | SPI | 80.56 | 1,699.56 | 15,890.68 | 4,563.66 | 566.02 | 1,500 | 139.30 | 11,364.04 | 2,528 | 39,331.82 | 82,320 | 27,780 | 110,100 |

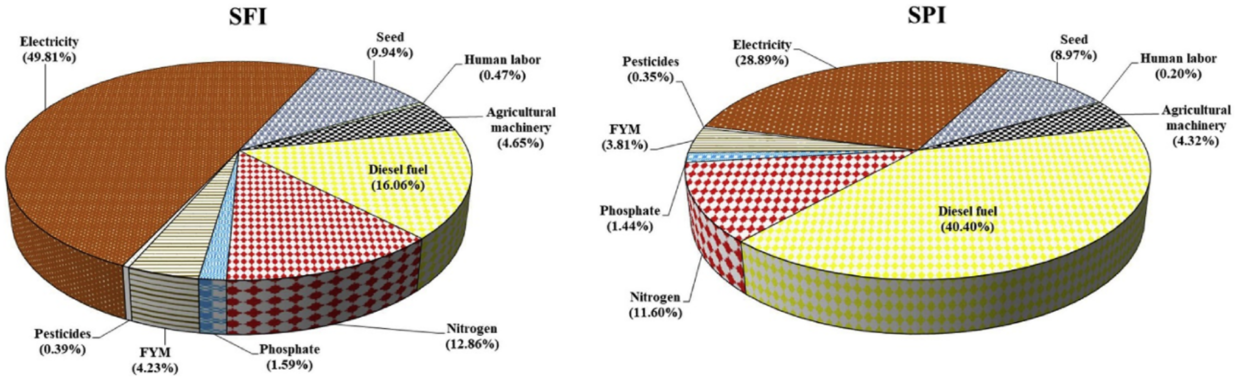

**Figure 25** | Share of energy inputs for SFI and SPI scenarios.

environmental perspective, the surface irrigation method paired with PV panels (SFI-PV) emerged as the most favourable option since it has the least environmental damage.

In a study conducted by Chahartaghi & Nikzad (2021), various technical parameters related to solar water pumping for irrigating a 1-ha potato farm located in Isfahan, Iran, were thoroughly investigated. These parameters encompassed aspects such as PV panel temperature, panel arrangements, efficiency, output power, pump speed, and the pump's output flow rate. Additionally, the study included an assessment of the exergy efficiency of the PVWPS. The investigation considered different water requirements throughout the crop growth period, spanning 130 days from February 3 to June 14. To optimize the system, an ideal fixed tilt angle of 25° was calculated based on the maximum total average global irradiation during the irrigation months. The study's findings indicated that employing two parallel strings, each comprising 16 panels with a nominal power of 300 W per string, would be sufficient for the model. It was shown that when irradiation values are higher than 900 W/m$^2$, the influence of ambient temperature on pump outlet discharge is negligible. They also studied exergy efficiency as the ratio of total output to total input exergy of the system. For sensitivity analysis, solar irradiations of 600, 700, 800, 900, 1,000, and 1,100 W/m$^2$ were considered at different ambient temperatures of 10, 14, 18, 22, 26, and 30 °C. It was shown the maximum and minimum exergy efficiencies are 3.56 and 0.27%, much lower than the conventional values for PV electrical efficiency. In fact, the exergy efficiency for irradiations between 600 and 800 W/m$^2$ did not consistently exhibit upward or downward trends. This is because while an irradiation improvement at a constant ambient temperature consistently leads to a great rise in input exergy, the corresponding increment in output exergy, however, is not as pronounced in that radiation range. Furthermore, from the environmental point of view, it was concluded that implementing the solar system could prevent the emission of 4.8 tons of $CO_2$ per year, equivalent to conserving 11.1 barrels of crude oil that would otherwise have been consumed. Notably, the study also evaluated the use of a sun tracker system and its financial implications. Ultimately, due to higher capital and operational costs, as well as increased system complexity and space requirements, the use of a sun tracker system was not deemed suitable for their model. In another investigation conducted in the same year by Heydari *et al.* (2021), the feasibility of solar water pumping was assessed in three provinces: North Khorasan, Khorasan Razavi, and South Khorasan. This assessment was carried out using a multi-criteria-decision-making method. The researchers considered a total of 93 sites across these three provinces and applied 15 significant criteria, including factors like solar irradiation, wind speed, precipitation, distance from the river, and proximity to the grid. Each criterion was weighted using the Shannon entropy method. This technique uses a criterion–option matrix, as introduced by Shannon *et al.* (2008), to measure the uncertainty level of a continuous probability distribution. The main concept of this method is that a criterion with high dispersion is supposed to have significant importance. Thirty different sensitivity analyses were done to ensure the reliability of the results. The study revealed that Sarayan was identified as the most suitable site for establishing a standalone water pumping station in 28 out of 30 analyses. The second-best site was found to be Isk station. They concluded that these results provide a practical framework for selecting the most suitable site within a region for implementing a solar water pumping project.

In 2022, Jahanfar and Tariq Iqbal presented the main findings of their research in two conferences. In the first article (Jahanfar & Iqbal 2022a), optimization of the size of the hybrid (Battery + Water tank) system was done by using HOMER Pro. The design of a reliable system with adequate storage and minimum life cycle cost. A 2-ha cherry and apple garden near Mashhad city, northeast of Iran was selected where a conventional diesel generator was the energy source for

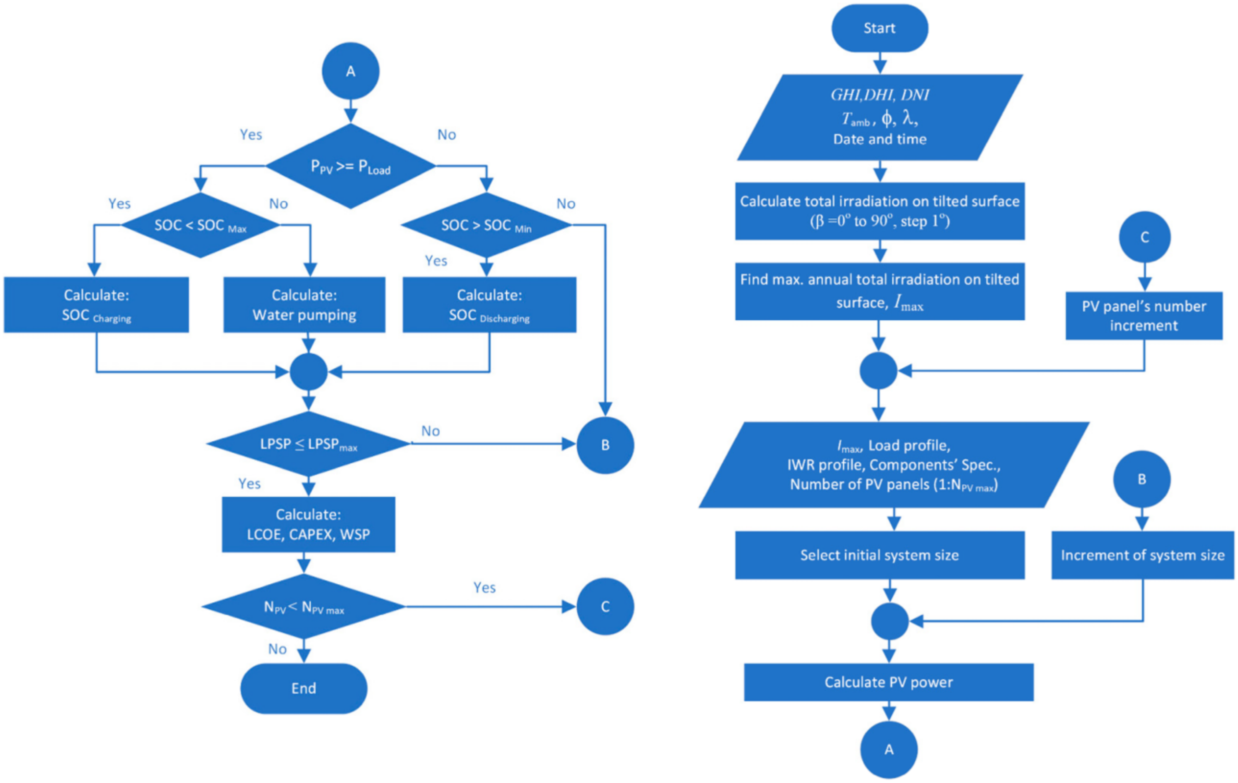

**Figure 26** | The PVWPS algorithm used in reference (Irandoostshahrestani & Rousse 2023).

providing about 180 $m^3$ of water per day. The Imperialist Competitive Algorithm (ICA) was used as the optimization tool for replacing the current conventional system with PVWPS. This algorithm was first developed by Atashpaz Gargari (Atashpaz-Gargari & Lucas 2007) and it works by selecting an initial point at random, named a 'country'. These countries are then divided into two sets: imperialists and colonies, with each colony being affiliated with an imperialist. Then, imperialists participate in a competition among themselves to acquire control over more colonies. Finally, the most dominant imperialists take control of all countries, guiding them towards an optimal state. The results of the optimization analysis led to a system with 40 batteries (each 100 Ah) and 140 $m^3$ of water tank with approximately 20,000 CAD total cost. In the second article (Jahanfar & Iqbal 2022b), they evaluated the reliability of a PVWPS in the hybrid storage mode of the battery bank system and water tank. The hybrid storage system proposed in the previous study was shown to be a cost-effective solution to assure the system's operation even in zero or low irradiations. They used MATLAB Simulink to study the dynamic

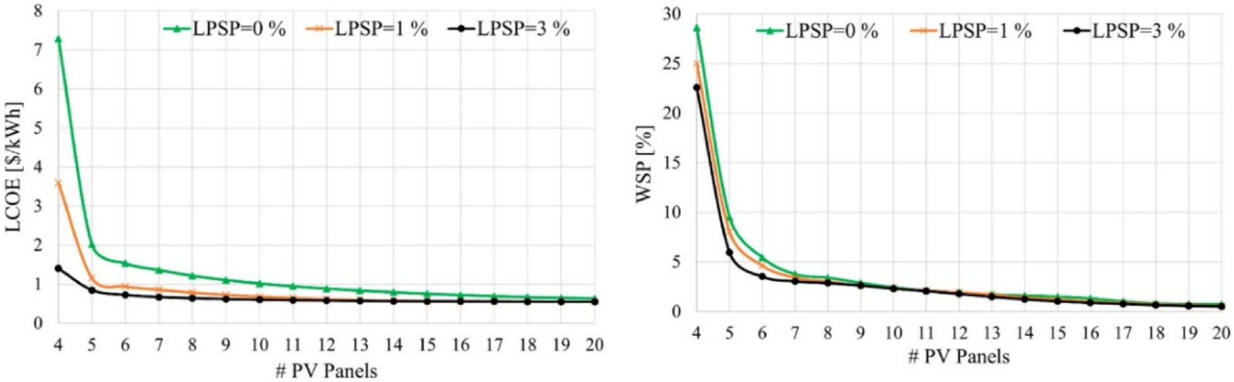

**Figure 27** | Variations of LCOE and WSP with PV panel numbers at different LPSPs (Irandoostshahrestani & Rousse 2023).

**Table 8** | Summary of studies regarding solar water pumping in Iran

| # | – Author(s)<br>– Location<br>– Year | Application/study type | Methodology | – Battery<br>– Cooling | PV:<br>– Efficiency<br>– Panel model<br>– Nominal power | Motor-pump:<br>– Efficiency<br>– Model<br>– Head<br>– Flow rate | Highlights |
|---|---|---|---|---|---|---|---|
| 1 | – Abdolzadeh, Ameri, and Mehrabian<br>– Kerman<br>– 2006 | Efficiency improvement of SWPS by cooling | Experimental setup | – No<br>– Water spray | – 13.5%<br>– Not provided<br>– Three panels each 45 W | – Not provided<br>– PS150 Boost<br>– 45 m (max)<br>– 850 L/h (max) | Maximum improvement in pumping volumetric flow rate of around 40% in the case with three PV panels (135 W) with 25 L/h per module water spray at a head of 16 m. |
| 2 | – Abdolzadeh, Ameri, and Mehrabian<br>– Kerman<br>– 2006 | Effect of operating head on PVWPS | Experimental setup | – No<br>– No | – 12.5%<br>– Not provided<br>– Two or three panels each 45 W | – Not provided<br>– PS150 Boost<br>– 45 m (max)<br>– 850 L/h (max) | Two essential factors for the design of PVWPS are achieving the maximum power relevant to the chosen operating head and meeting the consumer needs. Successfully considering both criteria contribute to the design of systems with minimized capital costs. |
| 3 | – Kordzadeh<br>– Kerman, Kerman<br>– 2010 | To increase the efficiency of the panel through thermal management | Experimental setup | – No<br>– Thin continuous water film | – Not provided<br>– Not provided<br>– Two or three panels each 45 W | – Not provided<br>– PS150 Boost Lorentz<br>– 45 m (max)<br>– 1,000 L/h (max) | Decrement of nominal power and increment of system head positively impact the PV efficiency and the system. Thin water layer on the panel enhances the efficiency of the panel and consequently the system especially in low nominal powers of the panel. |
| 4 | – Tabaei and Ameri<br>– Kerman, Kerman<br>– 2012 | To improve the performance of the SWPS system by using booster reflectors | Experimental setup | – No<br>– No | – Not provided<br>– Not provided<br>– Not provided | – Not provided<br>– PS150 Boost<br>– 45 m (max)<br>– 1,000 L/h (max) | Increase in output power of the panel by about 14% for aluminium foil reflector and 8.5% for stainless steel 304 reflector. Furthermore, 18% increase in pump flow rates with the aluminium foil reflector and a 9% increase for the stainless-steel reflector. The superiority of aluminium foil was due to its higher reflectivity characteristics. |
| 5 | – Rezae and Gholamian<br>– Golestan, Gorgan<br>– 2013 | Farmland irrigation | Numerical (RETScreen) | – ATLAS BX (12 V-100 Ah)<br>– No | – 16.4%<br>– SANYO HIT Power 195 BA20<br>– Fifteen panels each 195 W | – 62% (motor-pump)<br>– MOTOGEN-CR90L2A electromotor<br>– 16 m<br>– 200 $m^3$/day | Adoption of solar water pumping systems for irrigation can result in considerable cost savings in the long term; however, incentives by the government like loans are necessary to encourage people to use them. The payback period was calculated to be 14 and 6 years for subsidized gasoil by the government and FOB Persian Gulf price, respectively. |

(*Continued.*)

**Table 8** | Continued

| # | – Author(s)<br>– Location<br>– Year | Application/study type | Methodology | – Battery<br>– Cooling | PV:<br>– Efficiency<br>– Panel model<br>– Nominal power | Motor-pump:<br>– Efficiency<br>– Model<br>– Head<br>– Flow rate | Highlights |
|---|---|---|---|---|---|---|---|
| 6 | – Habiballahi, Ameri, and Mansouri<br>– Kerman, Kerman<br>– 2015 | Efficiency improvement of SWPS by cooling | Experimental setup | – No<br>– Collectors beneath the panel | – 13.5%<br>– Not provided<br>– Three panels each 45 W | – Not provided<br>– PS150 Boost<br>– 45 m (max)<br>– 850 L/h (max) | About 20% improvement in mean power and 29% increase in mean water flow rate occurred due to cooling by collectors beneath the panels at Head = 16 m and a collector mass flow rate of 310 L/h. |
| 7 | – Tabaei and Ameri<br>– Kerman, Kerman<br>– 2015 | Improving the effectiveness of a SWPS by cooling and booster reflector | Experimental setup | – No<br>– Continuous film of water | – Not provided<br>– Not provided<br>– Three panels each 45 W | – Not provided<br>– PS150 Boost<br>– 45 m (max)<br>– 1,000 L/h (max) | Applying both booster reflector and PV cooling with a film of water for a SWPS revealed a maximum of 50.4% increment in output power of the panels at a head of 16 m. |
| 8 | – Mohammadi<br>– South of Iran<br>– 2015 | Irrigation and drinking for remote areas | Mathematical optimization | – No<br>– No | – Not provided<br>– Not provided<br>– Two to five panels each 55 W | – Not provided<br>– Not provided<br>– Not provided<br>– 56 $m^3$/day | Finding an optimized solution for two factors of LLP and life cycle cost of the system with Pareto solutions that provides flexibility for the user to choose between different plans. |
| 9 | – Niajalili *et al.*<br>– Gilan, Rasht<br>– 2017 | Rice paddy | Experimental setup | – L16RE-B (6 V-370 Ah)<br>– No | – 13.7%<br>– LG220P1C<br>– Two panels each 220 W | – Not provided<br>– Pedrollo, Centrifugal pump HFm 50B<br>– 10 m (max)<br>– 300 L/min (max) | SWPS is a good option in Gilan since there are enough water and irradiation. The field area mandates the size of the system in terms of panel area and pumping power. SWPS becomes feasible after 9 years compared to conventional gasoline-powered pumping systems. Conventional pumping systems cost 1.5 times SWPS in the project lifetime (25 years). |
| 10 | – Shirinabadi, Samadi Saray, and Maanifar<br>– Tabriz<br>– 2018 | 800 kW water pumping power plant | Numerical (PVSYST) | – No<br>– No | – Not provided<br>– YL300P-35b<br>– 2,670 panels each 300 W | – Not provided<br>– Horizontal centrifuge<br>– Not provided<br>– 342 L/s | Feasibility of replacing a conventional grid-based water pumping station with 1,000 W pumping capacity with PVWPS was evaluated successfully. It was shown that the proposed system can avoid emission of approximately 509 tons of $CO_2$-eq per year. |
| 11 | – Parvaresh Rizi, Ashrafzadeh, and Ramezani<br>– Fars, Jahrom and Khorasan Razavi, Kashmar<br>– 2019 | Citrus orchard and Vineyard | Mathematical modelling | – Yes<br>– No | – Not provided<br>– Not provided<br>– Between 56 and 90 panels each 80.5 W | – Solar pump:<br>– Not provided<br>– DC<br>– 40 m (max)<br>– 23 $m^3$/h (max)<br>– Diesel:<br>– Not provided<br>– RobinPKX320 | The financial analysis of three different sources of energy for irrigation (i.e., solar, electricity, diesel) showed that the economic viability depends on different parameters of annual electricity cost, distance from the electricity grid, availability of pumps and other instruments, irrigation power required, fuel supply and its |

(*Continued.*)

**Table 8** | Continued

| # | – Author(s)<br>– Location<br>– Year | Application/study type | Methodology | – Battery<br>– Cooling | PV:<br>– Efficiency<br>– Panel model<br>– Nominal power | Motor-pump:<br>– Efficiency<br>– Model<br>– Head<br>– Flow rate | Highlights |
|---|---|---|---|---|---|---|---|
| | | | | | | – 28 m (max)<br>– 66 $m^3/h$ (max)<br>– Electric:<br>– 56%<br>– WKL50<br>– 28 m (max)<br>– 20 $m^3/h$ (max) | price, etc. Due to subsidized electricity and fuel in Iran, solar pumping would be feasible through more incentives and policies by the government. |
| 12 | – Chahartaghi, Mehdi, and Jaloodar<br>– Mazandarn, Gharakhil<br>– 2019 | Drip irrigation | Mathematical modelling | – No<br>– No | – 15%<br>– Not provided<br>– Not provided | – Not provided<br>– Not provided<br>– 12 m (static head)<br>– Not provided | The system achieved its maximum water discharge when the solar panels were tilted at angles close to the latitude. More specifically, at a tilt angle of 41°. |
| 13 | – Mohammad Zamanlou, Tariq Iqbal<br>– West Azarbaijan, Urmia<br>– 2019 | Grape garden irrigation | Numerical (CropWat, Lorentz Compass 3, HOMER Pro, MATLAB Simulink) | – Trojan SAGM 12 V 105 Ah<br>– No | – 13%<br>– Canadian Solar 300CS6X<br>– 300 W | – 63% (max)<br>– Lorentz PS2-1800 C-SJ8-7<br>– 40 m (max)<br>– 13 $m^3/h$ (max) | – Feasibility study showed the successful application of PV-Battery-MPPT system for irrigation of 2.36-ha grape garden to total dynamic head of about 27 m with 24,000 CAD total cost. |
| 14 | – Nikzad, Chahartaghi and Ahmadi<br>– Mazandaran, Sari<br>– 2019 | Rice paddy irrigation | Numerical (PVSYST) Experimental (noise measurements) | – Trojan SAGM 12 V 205 Ah<br>– No | – 15.13%<br>– Lorentz, LCM100-M36<br>– 100 W | – Solar pump:<br>– 48% (motor-pump)<br>– Lorentz PS2e600C-SJ8-5<br>– 15 m (max)<br>– 12 $m^3/h$ (max)<br>– Diesel engine:<br>– Not provided<br>– KUBOTA RT100 DI<br>– Not applicable<br>– Not applicable | The CAPEX of the on-grid system is 2.41 times that of the conventional one. While over the 20-year operational period, the life cycle cost of the conventional system is more than that of the on-grid one by a factor of 2.89. On the contrary, the CAPEX of the off-grid model is 2.14 times that of the conventional one. In addition, over 20 years of operation, the life cycle cost of the conventional system is only 1.30 times that of the off-grid model. |
| 15 | – Shayeteh, Reihaneh and Moghaddam | | Numerical (MATLAB) | – No<br>– No | – 12.56% | – 51% pump, 82% motor | The optimized configuration based on tilt angle and azimuth angle showed about 19% |

(*Continued.*)

**Table 8** | Continued

| # | – Author(s)<br>– Location<br>– Year | Application/study type | Methodology | – Battery<br>– Cooling | PV:<br>– Efficiency<br>– Panel model<br>– Nominal power | Motor-pump:<br>– Efficiency<br>– Model<br>– Head<br>– Flow rate | Highlights |
|---|---|---|---|---|---|---|---|
| | – Bojnurd, North Khorasan<br>– 2020 | Water supply for irrigation and drinking | | | – TDB 125X125-72-P<br>– 160 W | – URD 152.9 PUMPIRAN<br>– 45 m (max)<br>– 12.6 $m^3/h$ (max) | lower total cost of the project compared to an existing system without optimization. |
| 16 | – Ghasemi-Mobtaker *et al.*<br>– Central part of Hamedan province<br>– 2020 | Use of PVWPS in two irrigation scenarios: surface irrigation (SFI) and sprinkler irrigation (SPI) | Numerical (TRNSYS) | – No<br>– No | – Not provided<br>– ND AH325<br>– 325 W | – Overall efficiency of 18–22%<br>– Not provided<br>– Not provided<br>– Not provided | The maximum photovoltaic power needed for replacement in SFI and SPI systems are 4.55 and 5.20 kW, respectively, for a 100-ha barley farm in Hamedan. SPI resulted in substantial $CO_2$ emissions equal to 1,184 kg/ha compared to 425 kg/ha for SFI. Furthermore, the SFI method paired with PV panels emerged as the most favourable technique due to its minimum environmental damage. |
| 17 | – Chahartaghi and Nikzad<br>– Isfahan, Isfahan<br>– 2021 | Potato farm irrigation | Numerical (COMPASS, RETScreen, PVsyst) | – Battery<br>– Natural convection by free air | – 15.46%<br>– Polycrystalline silicon<br>– 300 W | – Pump: 85% (max), Motor: 64% (max)<br>– Not provided<br>– 80 m (max)<br>– 25 $m^3/h$ (max) | The maximum and minimum exergy efficiencies were 3.56 and 0.27%. Furthermore, it was shown that the use of PVSWP could prevent the emission of 4.8 tons of $CO_2$ annually for a 1-ha potato farm in Isfahan. Finally, the use of a sun tracker was not suggested due to its high capital and operational costs and due to adding to the complexity of the system. |
| 18 | – Heydari *et al.*<br>– North/Razavi/South Khorasan<br>– 2021 | Solar water pumping station | Numerical | – No<br>– No | – Not provided<br>– Not provided<br>– Not provided | – Not provided<br>– Not provided<br>– Not provided<br>– Not provided | Selection of a solar water pumping station among 93 sites in the northeast and east of Iran based on 15 criteria provided a practical framework for selecting the most suitable site for implementing a PVWPS project. |
| 19 | – Jahanfar and Iqbal<br>– Near Mashhad<br>– 2022 | Irrigation of a 2.2-ha cherry and apple farm | Numerical (HOMER Pro) | – Yes<br>– No | – Not provided<br>– JC-340-72P<br>– 340 W | – Not provided<br>– Lorentz PSK2-40 | Feasibility study and optimization of a hybrid PV-battery-tank solar water pumping analysis led to a cost-effective system with 40 batteries (each 100 Ah) and 140 $m^3$ of |

(*Continued.*)

**Table 8** | Continued

| # | – Author(s)<br>– Location<br>– Year | Application/study type | Methodology | – Battery<br>– Cooling | PV:<br>– Efficiency<br>– Panel model<br>– Nominal power | Motor-pump:<br>– Efficiency<br>– Model<br>– Head<br>– Flow rate | Highlights |
|---|---|---|---|---|---|---|---|
| | | | | | | – 170 m (Total dynamic head)<br>– 27 $m^3$/h | water tank with around 20,000 CAD total cost. |
| 20 | – Jahanfar and Iqbal<br>– Near Mashhad<br>– 2022 | Irrigation of a 2.2-ha cherry and apple farm | Numerical (MATLAB Simulink) | – Yes<br>– No | – Not provided<br>– JC-340-72P<br>– 140 panels each 340 W | – Not provided<br>– Lorentz PSK2-40<br>– 170 m (Total dynamic head)<br>– 27 $m^3$/h | Dynamic analysis of a hybrid PVWPS with battery bank and water tank with MATLAB Simulink for a garden showed the stability of the system in different weather conditions and different load demands. It was shown that temperature variations do not change the stability of the system and the proposed hybrid PVSWP can be used for any city in the country. |
| 21 | – -Irandoostshahrestani and R. Rousse<br>– Bandar Abbas<br>– 2023 | Irrigation of a citrus farm | Numerical (MATLAB) | – 8A31DT-DEKA (12 V 104 Ah)<br>– No | – CS3K-305MS<br>– 18.36%<br>– 305 W | – Pump (90%)<br>– Not provided<br>– 8 m (Total head)<br>– Not provided | A small increase in power loss tolerance can greatly decrease the system's size, CAPEX, and LCOE, with minimum impact on WSP. This implies that communities with limited financial resources should explore additional strategies to prevent irrigation water shortage. |

response of the system in different conditions of load changes and temperature variations and showed that the proposed system is stable in variable weather conditions. It was shown that temperature variations do not considerably affect the system's performance.

Irandoostshahrestani & Rousse (2023) developed a MATLAB code for the evaluation of PVWPS in the south of Iran, in Bandar Abbas city. The algorithm was designed in order to provide power for a rural house with typical load demand and to charge the batteries when the residential load demand is met and finally, to run a water pumping system in case the batteries are full with the excess electricity produced by the PV panels. Details about the algorithm can be seen in Figure 26. The pumped water was aimed to irrigate a citrus farm with an area of 1 ha and a bell-shaped irrigation water requirement profile in different months of the year. The total dynamic head was set to 8 m and monocrystalline panels with a nominal power of 305 W were used. They used WSP and LPSP concepts in their design. Different configurations with various installed battery capacities and PV panels were suggested. They concluded that the selection of the best configuration depends on the WSP and LPSP tolerance of the users. In fact, a slight increment of power loss tolerance can considerably decrease the system's size, capital cost, and LCOE, with minimal effect on WSP. This implies that users with constrained financial resources have to explore additional plans to prevent irrigation water shortage. It was also concluded that there exists a minimum point on the CAPEX versus PV panels number diagram. Limited changes in WSP and LCOE occur with additional increments in the panel number. This is attributed to the rapid increase in battery bank requirements lower than the minimal panel numbers (Figure 27).

### 6.2. Summary of the PVWPS in Iran

To facilitate a comprehensive comparison of these studies, we have summarized them in Table 8. It's evident that only a few investigations have thoroughly explored solar water pumping from technical, financial, and environmental perspectives. Additionally, no study has explored the social implications of farmers adopting solar water pumping systems. Many of these research endeavours have been conducted in recent years, as shown in Figure 28. The cumulative number of studies illustrates a notable increase in the exploration of solar water pumping in Iran over the past few years. Nearly all these studies have either involved experimental setups or numerical simulations, primarily focusing on the feasibility study of agricultural irrigation. While not every region of the country has been examined for solar water pumping, the research has covered a wide array of locations across the nation, as depicted in Figure 29. It's worth noting that the red line in the southern areas of Iran corresponds to research (Mohammadi 2015), which did not specify the exact location of the study. This diverse utilization of solar PV systems in different regions of the country can be attributed to Iran's substantial potential for harnessing solar

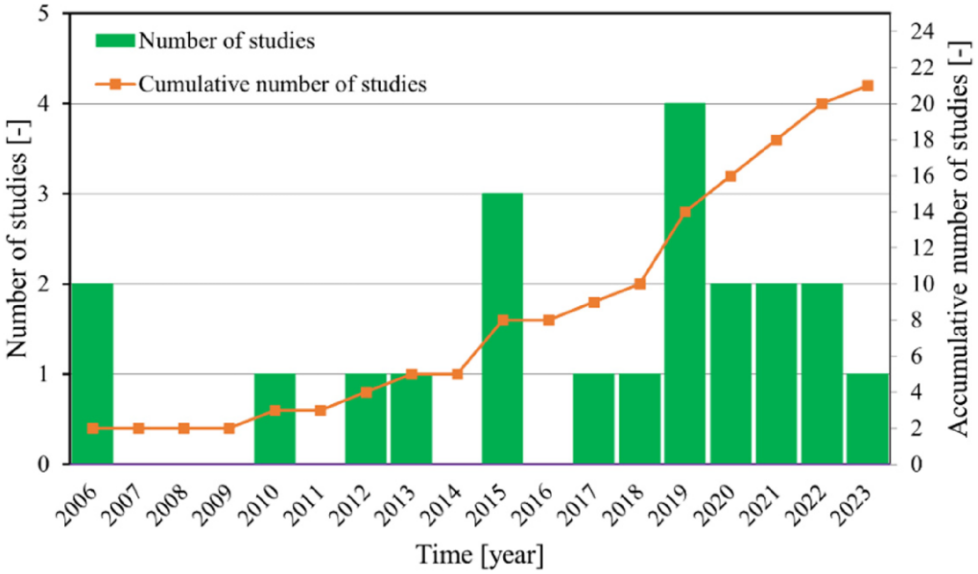

**Figure 28** | Number of studies in PVWPS in Iran.

**Figure 29** | Provinces of the studies relevant to PVWPS in Iran (reproduced from Wikipedia; Iran Location Map (2023)).

energy. Even in the northern regions with lower solar irradiation intensity compared to the southern and central areas, renewable energy solutions for water pumping remain a viable and attractive option.

## 7. CONCLUSIONS

This study investigates the current status of technologies and research related to solar PVWPS in Iran. Despite Iran's significant solar irradiation potential, there has been relatively limited research dedicated to solar water pumping systems. The existing studies encompass numerical, experimental, and theoretical approaches. To summarize the findings and the significance of the research, it can be concluded that:

- This comprehensive review emphasizes the growing interest and potential of harnessing solar energy for sustainable agriculture.
- One notable finding is the substantial reduction in $CO_2$ emissions, noise pollution, and savings in fossil fuels achieved through the implementation of solar water pumping systems, reaffirming their positive impact on both the environment and local economies.
- The research conducted in various provinces of Iran highlights the adaptability of solar water pumping across a range of different locations, from the sunny southern areas to the less irradiated northern provinces.
- While the initial capital costs of solar water pumping systems can be higher than conventional options, the sustained economic efficiency and substantial life cycle cost savings underscore the economic viability of renewable energy solutions.
- As Iran continues to invest in renewable energy infrastructure, addressing challenges such as fuel subsidies, interest rates, and Iranian Rial exchange rate fluctuations will play a crucial role in encouraging the extensive use of solar water pumping systems.
- The increase in research on solar water pumping in recent years reflects a growing awareness of the potential benefits of this technology.
- This review provides insights for policymakers, researchers, and farmers, showcasing the advantages of solar PVWPS and setting the stage for further innovation and implementation in the country's agricultural landscape.

As suggestions for future works, one can continue exploring technological innovations to enhance the efficiency of solar water pumping systems, conducting economic and environmental impact analyses, examining social and cultural aspects of technology adoption, and analysing policy frameworks to support sustainable implementation in Iran.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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