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A Review On Design And Performance Analysis Of Solar Photovoltaic Water Pumping Systems Technologies

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Abstract

This research aims to enhance the performance and reliability of Solar Photovoltaic Water Pumping Systems (SPVWPS) to promote their wider adoption in rural and agricultural settings. Solar PV systems offer a sustainable and eco-friendly solution for powering water pumps; however, their efficiency is influenced by factors such as solar irradiation, system design, and component quality. The study focuses on the development and implementation of optimization techniques, including Maximum Power Point Tracking (MPPT) algorithms, high-efficiency photovoltaic modules, and the optimal selection of motor and pump specifications. Key performance indicators such as cost-effectiveness, payback period, and energy efficiency are thoroughly analyzed with many approaches such as simulation software (PV syst). The research also emphasizes the importance of selecting suitable PV panels, power conditioning units, motors, and pumps. Technical evaluations of both stand-alone and grid-connected SPVWPS are presented, providing valuable insights for policymakers, researchers, manufacturers, and end-users in designing and deploying efficient solar-powered water pumping solutions.

Keywords: SPVWPS, maximum power point tracking, Motor, Pump

1. Introduction

Pumping systems are vital across a wide range of sectors, including oil, chemical processing, agriculture, sanitation, wastewater treatment, and water supply. They consume approximately 20% of the total electricity used in water treatment processes. As water resources become increasingly critical to meeting societal demands, efficient and reliable pumping solutions are essential [1]. In rural areas, where electricity supply is often unreliable and fuel costs are high, water supply for irrigation and communities heavily depends on alternative energy sources. Natural water sources are crucial for human survival, environmental sustainability, and agricultural productivity [2].

Traditionally, the majority of the world's water pumping needs are met using conventional electricity generated from fossil fuels. However, solar water pumping (SWP) offers a viable alternative that reduces dependence on fossil fuels [3]. Conventional fossil fuel-based pumping systems not only consume non-renewable resources but also contribute to air pollution and environmental degradation. Moreover, their associated costs—including fuel, operation, maintenance, and system replacement—tend to be higher compared to solar photovoltaic (PV)-powered pumps. Therefore, Solar Photovoltaic Water Pumping Systems (SPVWPS) present a sustainable and cost-effective alternative for the water supply and treatment sectors [4].

In developing countries, SPVWPS plays a crucial role in meeting the daily water demands of agriculture, livestock, and farming activities, accounting for approximately 19% of the total installed pumping capacity. These systems can operate in both stand-alone and grid-connected modes and are compatible with various energy storage technologies. Stand-alone solar PV systems are especially suited for remote regions with limited or no access to the conventional power grid, particularly in arid and semi-arid zones. Additionally, a detailed cost analysis of SPVWPS is illustrated in Figure 1 [5,6].

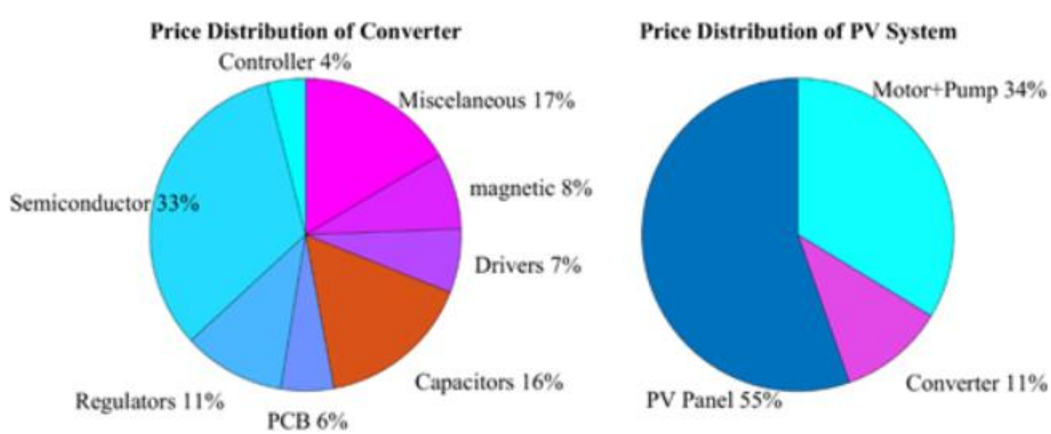

Figure 1: Cost analysis of the SPVWPS.

2. Photovoltaic System

Photovoltaic (PV) energy and other renewable energy sources are highly suitable for regions with moderate energy demands that are located far from the national power grid, due to their low operating costs and scalability [7,8]. PV systems generate electricity directly from sunlight without causing environmental harm. With ongoing advancements in efficiency and decreasing system costs, photovoltaic energy systems show strong potential for widespread adoption in the future [9,10]. However, the overall cost of energy generation remains relatively high, as PV technology is still in the early stages of development in some regions. The effectiveness of a PV system depends largely on the energy conversion efficiency of its components, particularly the PV panels. In many cases, practical systems still suffer from low overall efficiency.

To convert solar energy into usable alternating current (AC), a complete PV system typically includes a PV array, controllers, batteries, wiring, and an inverter, all working together. Several important insights have emerged from research on PV systems. Notably, the reliability of small, isolated power systems (SIPS) using PV depends significantly on geographic location [11]. The electrical output of PV modules is inversely related to their operating temperature, making them highly sensitive to local climatic conditions [12,13]. The strength and viability of solar renewable energy incentives depend on factors such as the size of financial incentives, the cost of residential PV installations, local electricity prices, and solar insolation levels.

As a result, accurate modeling of PV systems is essential for four key reasons: enhancing overall system efficiency, improving confidence in future energy production estimates, securing appropriate project financing, and streamlining system installation [14–16].

3.Solar Photovoltaic Water Pumping System

The Solar Photovoltaic Water Pumping System (SPWP) offers a sustainable and environmentally friendly solution for water pumping applications. A simplified schematic of the SPWP is presented in Figure 2.

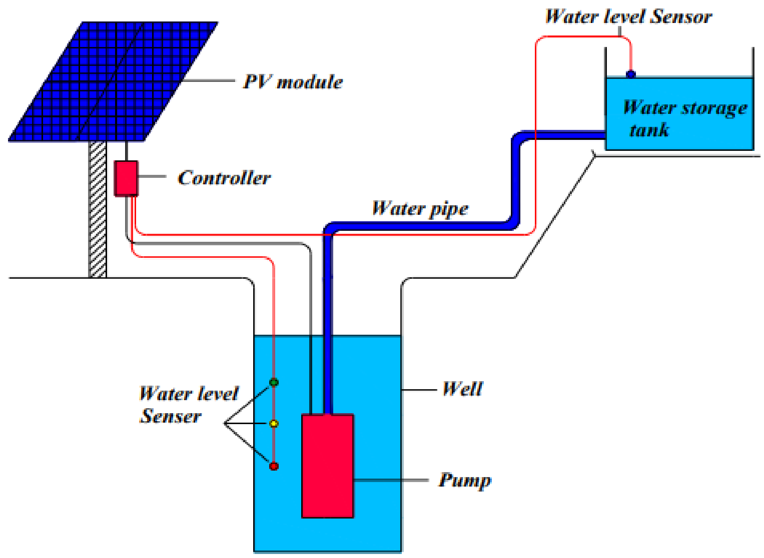

Figure 2: Schematic diagram of SPWP [17].

The primary components of a Solar Photovoltaic Water Pumping System (SPWP) include solar photovoltaic panels, a Maximum Power Point Tracking (MPPT) pump controller, a centrifugal surface pump, storage tanks, and pipelines.

- **Solar PV Panel:** Photovoltaic panels are available in various types, including monocrystalline, polycrystalline, thin-film, and the more recent and efficient bifacial panels [18]. The selection of a PV panel for water pumping applications depends on factors such as daily water requirements, the performance of the pumping system, and local solar irradiation.
- **Maximum Power Point Tracking (MPPT) Controller:** The MPPT controller optimizes the power transfer from the PV panels to the pump by using algorithms that continuously adjust the operating point to achieve maximum power output [19]. For optimal power transmission, the input impedance of the MPPT controller should ideally match the net impedance of the solar modules.
- **Centrifugal Surface Pump:** This type of pump is used to lift water from a lower elevation to a higher one or to generate continuous flow. It operates by using a motor to convert rotational energy into hydraulic energy in a moving fluid.
- **Pipes and Storage Tank:** Users can choose storage tanks and piping systems based on their specific needs. Pipe characteristics—such as material type, length, and the number of bends or elbows—can significantly affect slip losses and overall pumping efficiency [20].

An efficiency-based classification of solar PV modules is presented in Table 1. The overall efficiency of a solar water pumping system can be calculated using the equation provided in [21].

$$\eta_{total} = \eta_{PV} \times \eta_{MP} \quad (1)$$

Where,

$$\eta_{PV} = \frac{P_{PV}}{G_{GLOB} * A_{array}} * 100\% \qquad (2)$$

Where, P_{PV} is the PV array's maximum power under standard testing conditions, G_{GLOB} is the global sunlight radiance on a level surface [W/m^2]. A_{array} is the area of the solar array (m^2).

A simpler approach suggests using an easy-to-understand mathematical formula to estimate the solar panel's rated power via the usage of equation (3):

$$P_{PV} = I_{array} * V_{array} \qquad (3)$$

An electronic clamp meter can be used to realistically determine the voltage and current that exit the solar panel under full load conditions. Where, I_{array} is the current from the solar panel (Amp.) and V_{array} is the output voltages of the solar panel (Volt) [22]. Figure 3 shows the water flow rate during seasons.

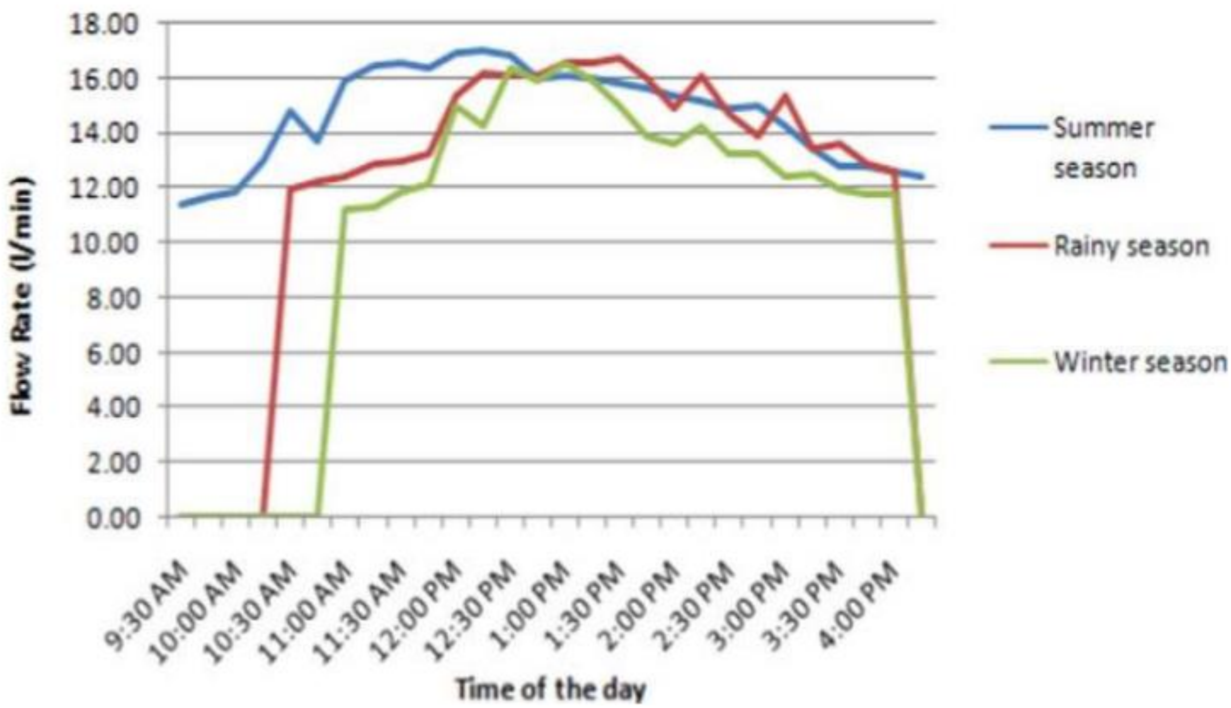

Figure 3: Water flow rate during seasons [23].

Table 1: Classification of solar PV modules [24].

Solar Cell Type	Efficiency	Merits	Demerits
Monocrystalline panel	20%	High rate of efficiency	Costly
Polycrystalline panel	15%	Low cost	Reduced lifespan, less space-efficient

Thin film amorphous silicon solar panels	7-10%	Easily customizable, cheap, and simple to manufacture	Restricted warranty and lifetime durations.
Concentrated PV cell	41%	Very high efficiency and productivity	It needs a solar tracker and a cooling system.

4. Electrical Machines for Solar Photovoltaic Water Pumping Systems (SPWPs)

The solar water pumping subsystem depends heavily on electrical machinery, which plays a critical role in system functionality. Electrical machines are devices that convert electrical energy into mechanical energy through the rotational motion of a shaft. In solar water pumping systems, the two primary types of motors used are Direct Current (DC) motors and induction motors. Each type has its specific advantages depending on the system design and application requirements. The classification of these motors is illustrated in Figure 4.

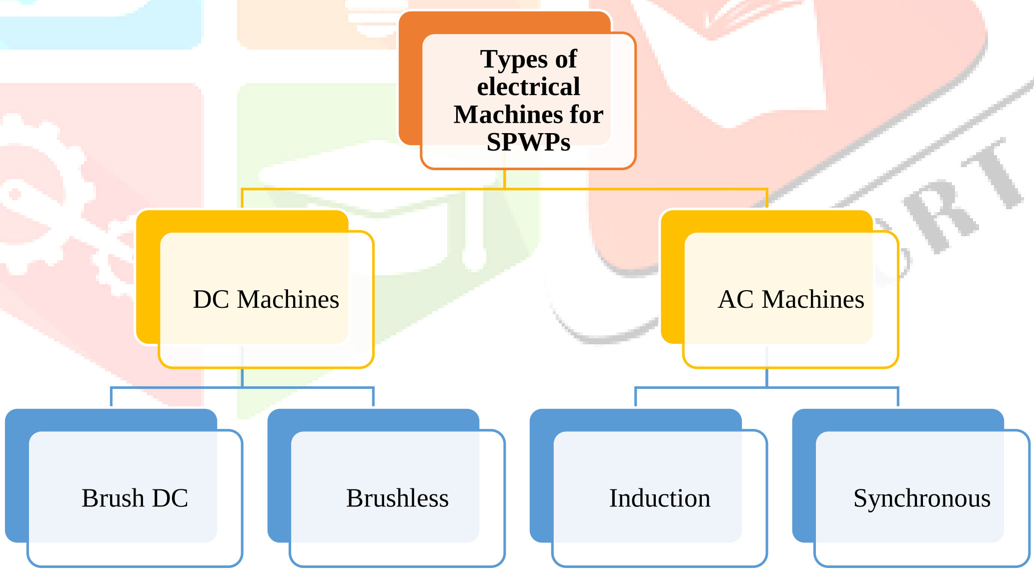

Figure 4: Main types of electrical machines for SPWP

Low-power Direct Current (DC) machines offer simple control and, in some cases, can be directly connected to the photovoltaic (PV) array, eliminating the need for costly power converters. One of the early studies on the use of DC motors for water pumping applications is documented in [25]. However, at higher power levels, DC machines become larger and more expensive due to the need for additional components such as commutating poles and compensation windings. A major drawback of DC machines is the presence of a commutator and brushes, which reduce mechanical reliability and increase maintenance costs—particularly problematic in moist or harsh environments. Additionally, most energy losses in a DC motor occur in the rotor, necessitating complex cooling systems at high power levels, which further limits the machine's overload capacity.

In contrast, induction machines with squirrel cage rotors are more advanced and offer superior performance compared to DC machines, especially in terms of power output and efficiency [26]. The primary loss in induction machines is copper loss. However, these machines maintain good efficiency at high speeds, as copper losses are reduced due to lower magnetizing current in the field-weakening region. With rapid advancements in power semiconductor technology, Alternating Current (AC) motors—particularly induction motors—have become increasingly preferred for solar water pumping systems over DC motors.

When selecting an appropriate electrical machine for a solar water pumping system, several factors should be considered, including system size, budget, power requirements, component availability, and maintenance history. The advantages and disadvantages of DC and AC machines are summarized in Tables 2 and 3.

Table 2: Advantages and disadvantages of DC machines

Advantages	**Disadvantages**
Both direct connection (no further control required) and DC-DC conversion are possible.	Requires maintenance because to insufficient brush life
Strong starting torque applied to the shaft	Cogging when rotating at low speeds
Versatile speed control (brush)	The energy dissipated because of the commutator
Several different controls for speed	Sparks can cause EMI
Quick response to changes in load	Possible failure of commutation
Optimal for pumping because of their speed-torque properties	Can be harmed in a humid atmosphere.

Table 3: Advantages and disadvantages of AC machines.

Advantages	Disadvantages
Low cost	Low starting torque value
Robust construction	High startup current
Availability of wide power range	Expensive control system
Relatively high-power factor	Cannot be directly connected to the PV array
Relatively high-power density	Efficiency drops at low loads
Does not need regular servicing	Performs badly at velocities lower than 30% of its official

The literature on SPWP systems describes several topologies, some of which include AC and DC machines (Table 4).

Table 4: Application of different electrical machines in solar- and grid-powered pumping systems.

Machine Type	Main Results
IM [27]	System efficiency increases with rising frequency, reaching its peak when the motor-pump operates at an optimal frequency, and both the flow rate and head are maximized.
IM [28]	The proposed method enables simultaneous execution of maximum power point tracking (MPPT) from the solar array, field-oriented control of the motor, and reduction of machine losses—streamlining the overall system performance.
BLDC [29]	No additional equipment was required for speed regulation. The integration of a DC link eliminates the need for a separate DC-DC converter, resulting in a more compact, cost-effective, and simplified system design. A PIC microcontroller is used to process signals from the electrical machine.
SynRM [30]	The efficiencies of the Synchronous Reluctance Motor (SynRM) and Induction Motor (IM) were evaluated through experimental testing using both a physical

	setup and MATLAB/Simulink modeling. Depending on the operating conditions, SynRM demonstrated an efficiency improvement ranging from 2% to 25%.
IM [31]	The study also investigates both single-pump and multi-pump systems based on induction motors. From an energy efficiency perspective, multi-pump systems offer greater advantages when operated under optimal load conditions.

5. State of the art in the SPVWPS

Solar Photovoltaic (PV) water heating systems are gaining widespread popularity due to recent technological advancements, including the availability of cost-effective and energy-efficient PV modules [32–34]. These innovations help reduce the initial investment cost [35] while offering extended operational lifespans [36–38]. Solar Photovoltaic Water Pumping Systems (SPVWPS) can be categorized based on several key criteria: grid connection type, power converter configuration, tracking system implementation, motor type, and pump design. This classification is illustrated in Figure 5.

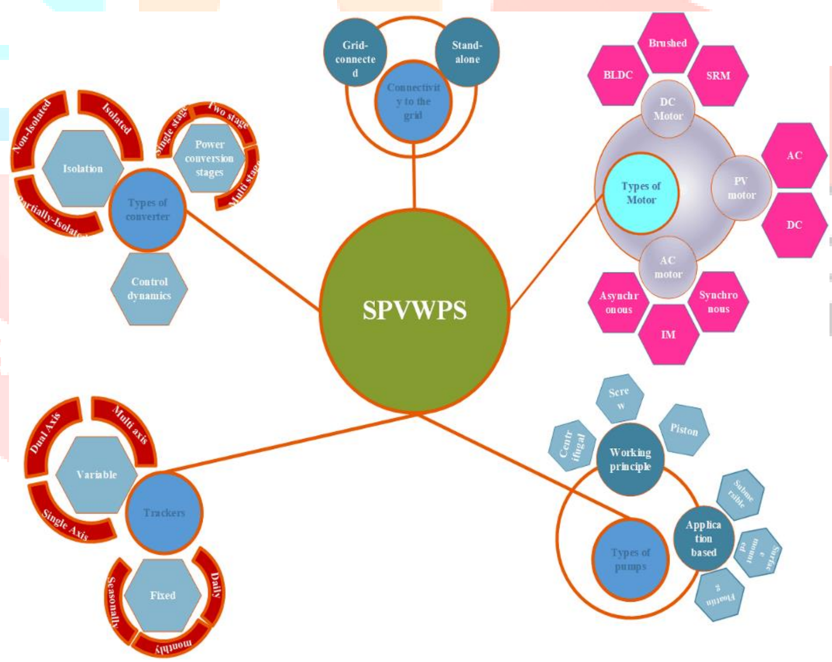

Figure 5: Classification of the SPVWPS

Traditional AC machines equipped with variable frequency drives (VFDs) have commonly been used by low- and medium-level farmers (LMLFs) with power demands below 5 kW. The peak solar hours (PSH) available in a day closely correspond to the water requirements for agricultural land—when PSH decreases, water demand increases, and vice versa. Additionally, the advanced technologies utilized in modern Solar Photovoltaic Water Pumping Systems (SPVWPS) are summarized in Table 5.

Table 5: State-of-art involving the SPVWPS

Author (Year) [Reference]	State-of-art used	Remarks
Yang et al., (2021) [39]	The sky-based feature extraction method has successfully predicted the short-term global horizontal irradiance.	A three-dimensional convolutional neural network is used by a machine learning method.
Boubaker et al., (2021) [40]	The Hammerstein autoregressive model gives an accurate short-term GHI prediction.	The approach combines swarm intelligence with dynamic non-linear modeling.
Ben Ammar et a., (2020) [41]	solar energy generation prediction using a neuro-fuzzy adaptive inference framework.	Whether data forecasting has been determined.
Condemi et al., (2021) [42]	Machine learning-powered hydropower forecasting considers reservoir supply and demand as well as changes in weather and meteorology.	ANN and SVM techniques are used.
Yaqub et al., (2019) [43]	The engine was remotely monitored and controlled at various water head levels with the help of a packet tracer simulator.	It is possible to regulate both the water level and the pumping procedure.
Rubio-Aliaga et al., (2019) [44]	A multi-dimensional analysis approach found that PV irrigation greatly reduces CO2 emissions and has a reduced computing time cost.	It is advised to do direct and periodic pumping depending on the amount of water, the depth of the water, and the crops planted there.

Piri et al., (2021) [45]	Monte-Carlo simulation and reliability analysis displayed from March to November under various efficiency factors assessed sewage water treatment pumping dependability. A 0.4 efficiency factor is more reliable, whereas 0.8 is more robust.	Results are better for ANN created using a genetic method based on machine learning.
Yamini et al., (2022) [46]	The analysis of hydraulic and flow patterns in pumps has shown that the design of the material determines the effectiveness of the pumping process.	The efficiency of the pumps can be enhanced by modifying the design structure.
Djeriou et al., (2018) [47]	An increased water pumping performance is shown by presenting the Golden Section Searches-based MPPT algorithm.	Enhancements are made to convergence time, free perturbation, and dynamic efficiency.
Shalaby et al., (2021) [48]	Optimal water pumping systems using fractional order fuzzy-based MPPT as compared to traditional approaches.	Using modified FL-MPPT, PSO, GWO, and ACO as benchmarks, the suggested technique is evaluated.
Dutta et al., (2020) [49]	Repairing water hammering issues is essential to preventing extensive damage.	The model predictive control approach is based on machine learning.
Shukla et al., (2021) [50]	A suggested WP that is powered by ANN-based DTC IM follows strictly the IEEE519 standard.	Power-sharing between PVWP and the utility grid is promoted.

Shayeten & Kardehi Moghaddam (2020) [51]	The multi-objective firefly algorithm proposed for azimuth and tilt angle optimization thereby achieves maximum efficiency.	The size of the overall system gets reduced, and profit is amplified.
Montero Dupont et al., (2018) [52]	Remote monitoring and supervisory control are implemented using the Raspberry Pi, considering all PV performance-affecting parameters.	Cloud-based monitoring without assigning a dedicated computer.
Naderipour et al., (2021) [53]	The probability of a non-water-supplied consumer is taken as the key objective in the intelligent water-dropping algorithm to size the PV pumping station.	Ensures reliable water supply with reduced NPC, including plantation costs.

Stand-alone and grid-connected photovoltaic water pumping (PV WP) systems typically employ induction motors (IMs) due to their widespread use in conventional setups and their lower cost compared to brushed DC motors. However, integrating PV systems with AC machines presents significant challenges, primarily due to the highly nonlinear characteristics of PV output and the complexity of controlling asynchronous AC motors. The coordination between the PV system and the motor control is intricate, which has motivated extensive research focused on improving this integration through advanced converter technologies. Various converter types used in water pumping systems are discussed in detail in Table 6.

Table 6: Various findings addressing water pumping technology

Author (Year)	Converter	Control algorithm	Motor-Pump	Finings
Kashif et al., (2021) [54]	Voltage source inverter	Adaptive hybrid generalized integrator (AHGI) with sliding mode observer	PMSM-centrifugal	Encoder-less PMSM control was introduced to avoid EM noise and temperature.
Mehazzem et al., (2021) [55]	Boost converter with SPVWM-controlled inverter	MPPT and IM backstepping control	IM-centrifugal	With fewer static errors and ripples, stability improved.
Khan et al., (2020) [56]	Inverter	Perturb & observe (PO) algorithm	IM-centrifugal	Optimum design of IM proposed for better speed regulation, dynamic response, etc.
Vamja & Mulla (2021) [57]	VSI	Modified second-order generalized integrator	IM-centrifugal	Errors caused by steady-state voltage variation and a low power factor should be kept to a minimum.
Rao et al., (2021) [58]	Five-level inverter	A level-shifted multi-carrier PWM	IM-centrifugal	The number of gate drivers and switches was reduced.

Murshid & Singh (2020) [59]	VSI	Mixed multi-generalized integrator	PMSM-centrifugal	Minimizing the number of sensors.
Rai et al., (2020) [60]	SVPWM controlled VSI	Improved PO, third-order integrator	IM-centrifugal	Instability is increased, and speed is increased.
Bhende et al., (2020) [61]	DC-DC converter, Inverter	Cooperative control	BLDC	Parallel operation of many units with power-sharing

6. Technical Aspects of SPWPS

A technical perspective of SPVWPS is outlined and it has been classified based on connectivity to the grid.

6.1 Based on connectivity to the grid

- **Stand-alone SPVWS**

Water pumping systems powered by solar PV technology without grid connection are known as autonomous, stand-alone, or islanded Solar Photovoltaic Water Pumping Systems (SPVWPS). These systems typically consist of a mounting structure for PV modules, the PV panels themselves, a charge controller, a battery, a motor, and a pump [62,63]. Stand-alone PV systems have been recommended for isolated or remote areas in Yemen to support rural electrification, with findings indicating higher initial costs but lower operation and maintenance expenses compared to alternative solutions [64]. The sizing and autonomy of these systems have been analyzed by considering the worst-case solar radiation hours, such as those in January. Additionally, the optimal design of the PV system has been detailed, accompanied by a comprehensive life cycle cost analysis comparing stand-alone PV systems to diesel generators (DG) [65]. The analysis reveals that the implementation cost for a stand-alone PV system is approximately 36 lakh INR, which is higher than that of a DG system for similar load demands. However, the study recommends PV installation based on net present value (NPV) theory for long-term sustainability due to its lower operation and maintenance costs.

Figure 6 illustrates three different configurations of stand-alone SPVWPS. Path 1 depicts a DC motor pump system. Path 2 shows a more economical setup where AC machines are directly coupled to the PV system without energy storage, though this configuration lacks reliability. Path 3 demonstrates the integration of existing machines with storage assistance, which can also be replaced by any suitable drive system to enhance performance and reliability.

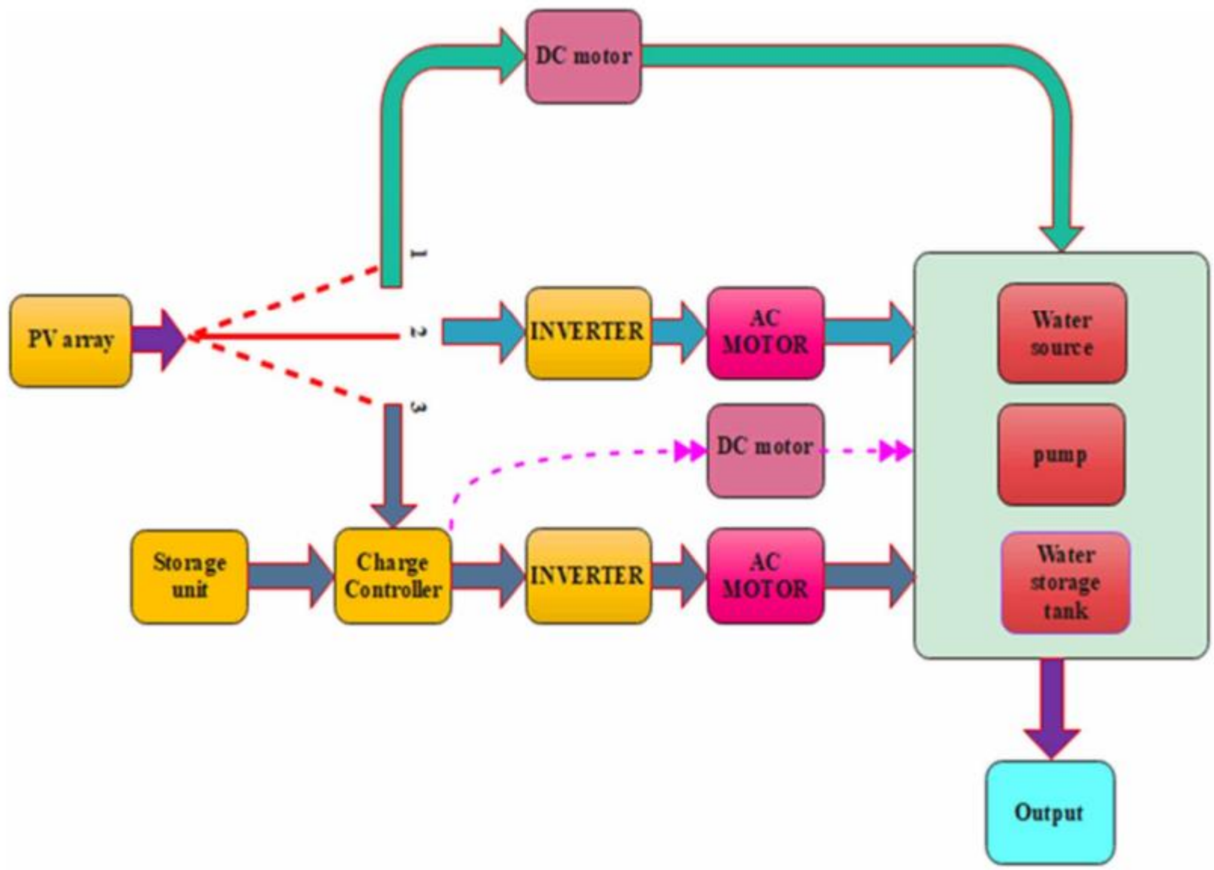

Figure 6: Design process in a stand-alone SPVWPS.

Table 7 aids in distinguishing between the various types of converters and MPPT techniques that are reported in the existing literature in the field of solar pumping systems and their verdicts are presented.

Table 7: Various findings in stand-alone SPVWPS

Authors (Year)	**Converter and MPPT used**	**Motor type**	**Overview of work**	**Research finding**
Singh & Mishra (2019) [66]	SIDO buck-boost converter	SRM	Drift-free operation under all insolation changes.	Flow controller introduced along with the MPPT helps to operate PV system as consumer-friendly

				operation and improves flexibility.
Vamja & Mulla (2020) [67]	Bidirectional DC-DC converter with VSI	IM	Developing storage assistance WPS acts as a utility during the night time.	Effective utilization of PV power.
Mishra & Singh (2018) [68]	Single switch dual output Zeta-derived DC-to-DC converter	SRM	Minimized cost and complexity and optimum operation of PV array	Continuous power supply with low ripple current.
Kumar & Singh (2015) [69]	Luo converter and IC	BLDC	Safe start of BLDC, maximum PV power extraction	120° CCM of fundamental frequency operation eliminates higher-order frequency switching losses and reduces stress.
Mishra & Singh (2017) [70]	Luo converter and IC	SRM	Developed a luo converter for a low-cost solar pumping system.	The proposed converter utilizes a split capacitor with fewer components, minimizing space for the heat sink.
Mishra & Singh (2019) [71]	High-gain single-ended	SRM	There has been a ripple effect in the	No need for a capacitor across the PV module,

	primary inductor converter		reduction of PV current.	3% enhancement of WPS was achieved.
Mufsina & Singh (2020) [72]	Modified DC-DC single-ended primary inductance converter (SEPIC)	SRM	In this study, they used MATLAB/Simulink to analyze the IC MPP approach and its performance.	At the same time as it gets rid of panel hotspot problems, it also gets rid of the difficulty of arraying solar panels for peak power.
Narayana et al., (2017) [73]	CSC-based midpoint converter	SRM	The drive's speed could be adjusted using the electronic commutation mode. A prototype was used to verify the converter's performance.	Low cost is a consequence of lower voltage and current stress on switches, which is made possible by the absence of sensors.

- **Grid Connected SPVWPS**

Power generation using solar photovoltaic (PV) technology combined with grid supply is referred to as grid-connected Solar Photovoltaic Water Pumping Systems (SPVWPS), which can operate without the need for battery storage.

All components present in stand-alone SPVWPS are also included in grid-connected systems; however, the latter connects to the utility grid, enhancing the distributed energy market by enabling customers to sell excess power to neighbors or the distribution company (DISCOM). This arrangement ensures continuous power availability whenever needed. In the absence of batteries, power system devices responsible for maintaining signal integrity, voltage stability, and dynamic stability become more complex, though overall system design complexity is reduced [74].

The power converter plays a critical role in grid-connected PV pumping systems, significantly influencing power quality, grid compliance, and reliability at the point of common coupling. Table 8 summarizes data from various published studies on water pumping applications, highlighting that different converter types involve varying stages of power conversion.

Bhende et al. (2020) [75] proposed a converter capable of operating SPVWPS in parallel with the grid and a locally connected Brushless DC (BLDC) motor. This converter prevents overspeed and sudden speed fluctuations in the BLDC motor, thereby ensuring a consistent water supply across all connected systems.

Table 8: Published studies on WP applications

Author (Year)	Converter and MPPT Used	Control approach	Motor Type	Grid side concern	Outcomes
Krishnakant & Kulkarni (2021) [76]	Two-level boost converter	—	BLDC and Loretz PS4000 CSJ8-15 centrifugal	Better synchronization	Every loss is considered when calculating demand.
Mishra & Singh (2021) [77]	Three-level boost converter	Second-order, third-order generalized integrator-based filter	4-phase SRM	Control over the voltage of the DC-link, preserving power quality and enhancing dynamic reactions.	Supports many modes of SRM-driven PVWP to the grid (no grid, no solar, solar power injecting to the grid when pumping not necessary, switching from solar-driven to grid-fed pump, transient analysis when pump halted in

					presence of both energies, switching from grid-fed to solar-driven).
Saxena et al., (2021) [78]	Model predictive control-based VSC	Second-order modified-dual generalized integrator	__	Voltage stabilization and ride-through functionality	IEEE-519 power quality standards are followed for optimal power management, improved ride-through operation, and power quality.
Kumar & Singh (2016) [79]	Power factor corrected buck-boost converter	__	BLDC	Preserving power factor and creating grid-supported PVWPS	Reduced sensor-based power flow management and power factor adjustment at the electric grid.
Mishra & Singh (2020) [80]	VSC with midpoint converter operated drive	P&O	SRM	Reduce the dc-link capacitor's size.	IEEE-519 standard is satisfied in all circumstances
Murshid & Singh (2020) [81]	Power factor–corrected buck-boost	HMRGI (hybrid multi-resonant generalized	PMSM	Abnormalities in the grid voltage and the WP's constant functioning	Improvement of PQ at grid terminals

	converter, VSI	integrator)-frequency-locked loop		regardless of the state of the grid.	
Makhdoomi & Askarzadeh (2020) [82]	Inverter	A method for differential crow searches	A centrifugal pump that changes speed	Reducing average operational expenses	Minimizing electricity consumption via the use of pumped hydro storage.
Singh & Gaur (2020) [83]	MPPT boost converter with configurable step size	Reduced complexity of direct torque control using space vector modulation	IM	Electricity transfers between two sources with a small ripple.	Faster settling time, excess power injection to the grid, and dependable pumping operation.

7. Efficiency of Solar Water Pumping Systems Using Motors and Pumps

- **Motors**

The motor and pump form the core components of any water pumping system. The practical selection of motor types depends on factors such as cost, availability, and power supply conditions. Key considerations when choosing a motor include its rating, efficiency, affordability, and accessibility. Consequently, research on the suitability of different motors against these criteria is ongoing. In real-world applications, conventional motors are often preferred over newer designs, with the induction motor (IM), or asynchronous motor, being the most widely used.

Figure 8 presents a classification of motor types suitable for water pumping applications. Examples of DC motors used in Solar Photovoltaic Water Pumping Systems (SPVWPS) include variable reluctance motors, brushed and brushless permanent magnet DC (PMDC) motors, while both synchronous and asynchronous AC motors are also utilized [84].

Although DC motors tend to be more expensive, they offer advantages in power conversion efficiency because they can be directly powered by the PV system. However, the presence of brushes in traditional DC motors reduces their reliability and lifespan, increasing maintenance costs. The development of brushless

DC motors provides a solution to these challenges by enhancing durability and reducing upkeep requirements [85]

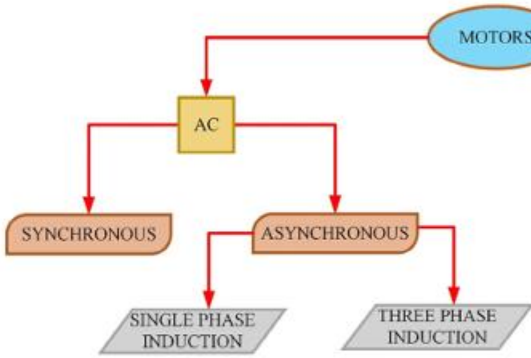

Figure 8: Classification of motor.

- **Pump**

In Solar Photovoltaic Water Pumping Systems (SPVWPS), pumps are a critical component that directly influences water delivery. The pump's primary function is to convert the kinetic energy supplied by the motor into hydraulic energy to move water. Pumps are commonly classified based on factors such as application, operating principle, installation depth, flow rate, capacity, cost, and market availability. Depending on the specific requirements, pumps may be submersible, surface-mounted, or floating.

Figure 9 illustrates the classification of pumps into two main categories based on their working principles: dynamic pumps and positive displacement pumps [86]. Dynamic pumps are further divided into axial flow pumps and centrifugal pumps, each available as submersible or surface variants. Positive displacement pumps include piston pumps and screw pumps as their primary subtypes [87].

The use of DC pumps in solar PV systems offers several advantages: (a) reduced power conversion losses, (b) improved operational efficiency typically seen in AC pumps, (c) enhanced reliability, and (d) the ability to operate effectively under temperate and low-irradiation conditions. To evaluate the overall system performance, a DC-powered SPVWPS has been designed and experimentally tested for efficiency

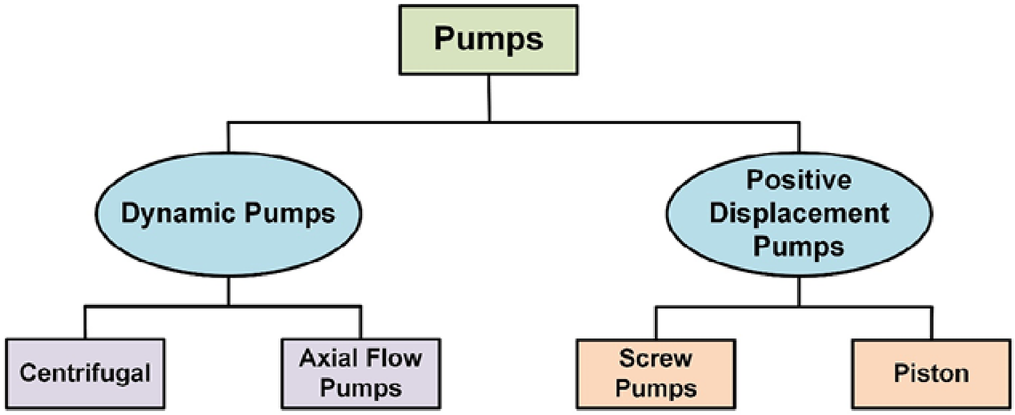

Figure 9: Classification of pumps

In Table 9 they can see the aggregate data and performance evaluations of most of the pumps.

Table 9: Evaluation of different pump types' performance

Authors	PV capacity (Wp)	Motor type	Pump type	Head (m)	Flow rate	Outcomes
Bouzidi (2013) [88]	__	DC	Centrifugal	18	Direct driven 24L/min, with buck converter 65.39L/min.	Compared to direct-coupled solar water pumping, which has a discharge head of 9 inches and a suction head of 18 inches, the buck converter achieved a greater water discharge rate of 65.39L/min.
Mokeddemet al., (2011) [89]	1500	PMDC	Centrifugal	11	35L/min	Centrifugal pumps are best suited for places with lower heads, such as distant locations.
Kolhe et al., (2004) [90]	720	PMDC	Centrifugal	5	38L/min	Results showed that PMDC with a centrifugal pump

						performed better in varying climates, with increased starting torque even in the presence of low irradiation. A 20% increase in output water compared to fixed axis monitoring is achieved by manually tracking the PV modules three times daily and adjusting their tilt angle.
Benghanem et al., (2013) [91]	1800	DC	Submersible helical pump	80	22 m3/day	Two appropriate PV configurations were chosen from four alternatives to give the ideal amount of energy for an outdoor-appropriate DC helical pump. By using 8S*3P PV array arrangements, a water production of 22 m3/day was attained.
Setiawan et al., (2014) [92]	3200	Asynchronous	Two submersible pumps	250	24-54Lmin	Two submersible pumps were powered from a depth of 250 m by 32 solar panels, which generated a total of 3200 Wp and allowed for a water

						flow rate of 0.4 to 0.9 L/s.
Korpale et al., (2016) [93]	2700	3 phase IM	Submersible	__	69 L/min with SPVWPS and 65 L/min with the previous system.	In terms of efficiency, PV-based SPVWPS outperformed the conventional water-pumping system by 39%.

8. Conclusion

The optimization of Solar Photovoltaic Water Pumping Systems (SPVWPS) offers significant potential to improve performance, efficiency, and sustainability in water supply applications. This study systematically reviews various optimization strategies and their impact on the effectiveness of PV water pumping systems.

Key optimization techniques such as Maximum Power Point Tracking (MPPT), system sizing, and component selection play a vital role in enhancing overall system efficiency and reliability. MPPT algorithms—including Perturb and Observe (P&O), Incremental Conductance (IC), and artificial intelligence (AI)-based methods—have demonstrated considerable success in maximizing power extraction from PV panels under fluctuating environmental conditions. These approaches ensure that the PV system operates consistently at its optimal power point, thereby increasing energy harvest and improving pumping efficiency.

System sizing, which involves the precise matching and selection of PV modules, pumps, and storage components, is another critical optimization factor. Proper sizing guarantees that the system meets water demand efficiently while minimizing energy losses and operational costs. The use of advanced simulation tools and software facilitates accurate system design, resulting in enhanced performance and cost-effectiveness.

Moreover, component selection—particularly the adoption of efficient and durable pumps—is crucial for the long-term sustainability of SPVWPS. Recent innovations in pump technology, such as high-efficiency DC pumps, have significantly boosted system performance. The integration of smart controllers and monitoring systems enables real-time performance tracking and adaptive control, further improving reliability and efficiency.

In conclusion, optimizing solar PV water pumping systems through advanced MPPT techniques, precise system sizing, and careful component selection effectively enhances system performance. These improvements support sustainable water resource management and promote wider adoption of renewable energy in water supply applications. Future research should focus on integrating emerging technologies like the Internet of Things (IoT) and machine learning to further automate and optimize PV water pumping systems, aiming for even greater efficiency and reliability.

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