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INTELLIGENT AND INTERNET OF THINGS (IOT)-ENABLED SOLAR WATER PUMPING SYSTEMS FOR OFF-GRID WATER SUPPLY: A SYSTEMATIC REVIEW OF AUTOMATION, PREDICTIVE CONTROL, AND REAL-TIME PERFORMANCE MONITORING

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Abstract: *Solar water pumping can be used to supply water to off-grid locations in rural areas, farms, and remote locations, although the evidence of intelligent and Internet of Things-enabled systems remains very dispersed. This is a systematic review that summarized 47 studies that were located using a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-based search of six academic databases. Decision-making locus, predictive capability, system architecture, and the method of validation were the classifications used to classify studies. The field deployments are few with evidence dominated by small-scale prototypes and simulations. There are typical combinations of low-cost microcontrollers, wireless sensors, and cloud/mobile dashboard. Reactive, threshold-based automation is the most common type of approach; predictive and machine-learning is less so, and is seldom incorporated into closed-loop control. Basic electrical and moisture parameters are usually monitored, and heterogeneous measures and lack of long-term testing inhibit reliability, economic viability, and adoption by the users. Overall, the field seems to be growing, yet it may be methodologically underdeveloped: connectivity seems to have grown faster than evidence of long-term, scaled benefits. Advances might need standardized performance levels, long field validation, interoperable and safe architectures and predictiveness architectures incorporated in closed loop operation.*

Keywords*: intelligent solar water pumping, Internet of Things, predictive control, closed-loop automation, off-grid water supply, performance monitoring.*

1. Introduction

A significant infrastructure challenge in rural and remote areas is to ensure water supply without connected electricity grid (Othman *et al*., 2021). For domestic supply of water, livestock and irrigation, solar water pumping is a scalable alternative, with the decreasing cost of PV and modular system design (Aliyu *et al*., 2018; Shinde & S, 2015). The system usually consists of a photovoltaic (PV) array, power conditioning, a motor-pump and a water storage and distribution.

The first solar pumping systems were manually operated or operated by a basic float switch. However, they seldom considered the variability of irradiance, the trend of water level in the tanks, pump condition and water demand change, which led to inefficient operation and insufficient fault awareness (Shepovalova *et al*., 2020).

With the advent of low-cost Internet of Things (IoT) sensors, wireless communication and embedded controllers are now used to monitor and automatically actuate. Cloud and mobile platforms enable remote supervision to be extended, and forecasting and optimisation can provide the potential to predict water demand and energy availability.

The increasing interest seems to be accompanied by apparently inconsistent evidence. A considerable number of studies have presented small prototypes or simulations, and only few studies have been field tested over long periods of time (Saraiva *et al*., 2025). There are also variations in the system scale, climate, sensing, control, and outcome metrics making it difficult to compare and assess practical benefits.

This review is driven by four gaps: first, there is a lack of consistency in the terminology used to describe the concepts of intelligence and autonomy; second, the ability to assess field evidence as opposed to simulation is

limited; third, recurring sensing, communication and control architectures are not mapped; and fourth, the current understanding of reliability, cost, cybersecurity and user acceptance for deployable systems is weak (Palermo *et al*., 2022).
This review brings together the concept, design, implementation and validation of intelligence in solar pumping. It creates a functional taxonomy of reactive automation, remote monitoring and predictive/adaptive control, appraises evidence strength, maps system architectures and identifies translational challenges and research priorities.

2. Methodology

2.1 Review Protocol

This review was performed using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol was established prior to screening, which included the research question, eligibility criteria, approach to search, extraction fields, and quality-appraisal approach. The Population, Intervention, Comparison, Outcome (PICO) approach was used to categorise the population (off-grid solar pumping), intervention (IoT, automation or intelligent control), comparisons (conventional or less-intelligent systems) and outcomes (water/energy performance, reliability and implementation).
The sources that were searched include six scholarly sources (IEEE Xplore, Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar). The sources were chosen to reflect engineering, control and energy and applied agricultural research, with Google Scholar as an additional discovery source.
Three concept blocks were combined in the search terms and these were solar/PV water pumping, intelligence, IoT, automation, monitoring or predictive control and off-grid, standalone, rural or remote applications. Boolean operators, database specific syntax applied (no year limits).

2.2 Analytical Framework and Thematic Categorization

Intelligence function, evidentiary characteristics were used to classify. Decision locus (embedded, local or cloud), autonomy (monitoring, reactive actuation or autonomous scheduling) and anticipation (reactive sensing, forecasting or learning) are captured in the framework. Studies were categorized as automated irrigation/water optimisation, IoT monitoring/remote control, predictive/adaptive control or under a residual category. Scale, climate, validation approach and system context were also captured by extraction.

2.3 Inclusion and Exclusion Criteria

Studies were selected based on consideration of studies which focused on intelligent or Internet of Things (IoT) enabled solar pumping for off-grid/standalone water supply and which reported system design, monitoring, automation, predictive control or outcome. If adequate technical data were available, primary experimental, simulation, case and field studies were considered as acceptable.
Studies in which the solar pumping was not present, they did not concern related systems, or they were abstract-only or opinion papers, duplicated or superseded previous works, or not sufficiently validated or they did not have relevant outcome to assess, were excluded.

2.4 Study Selection Process and Quality Appraisal

Searches returned 982 records. The deduplication resulted in 555 records left for title and abstract screening of which 415 were excluded. Of the 140 reports requested for full text 22 were not available and 118 were assessed for eligibility. A total of 71 reports were excluded as the assessment was based on the full text; in the end, 47 studies formed the final corpus. The selection flow is shown in figure 1.

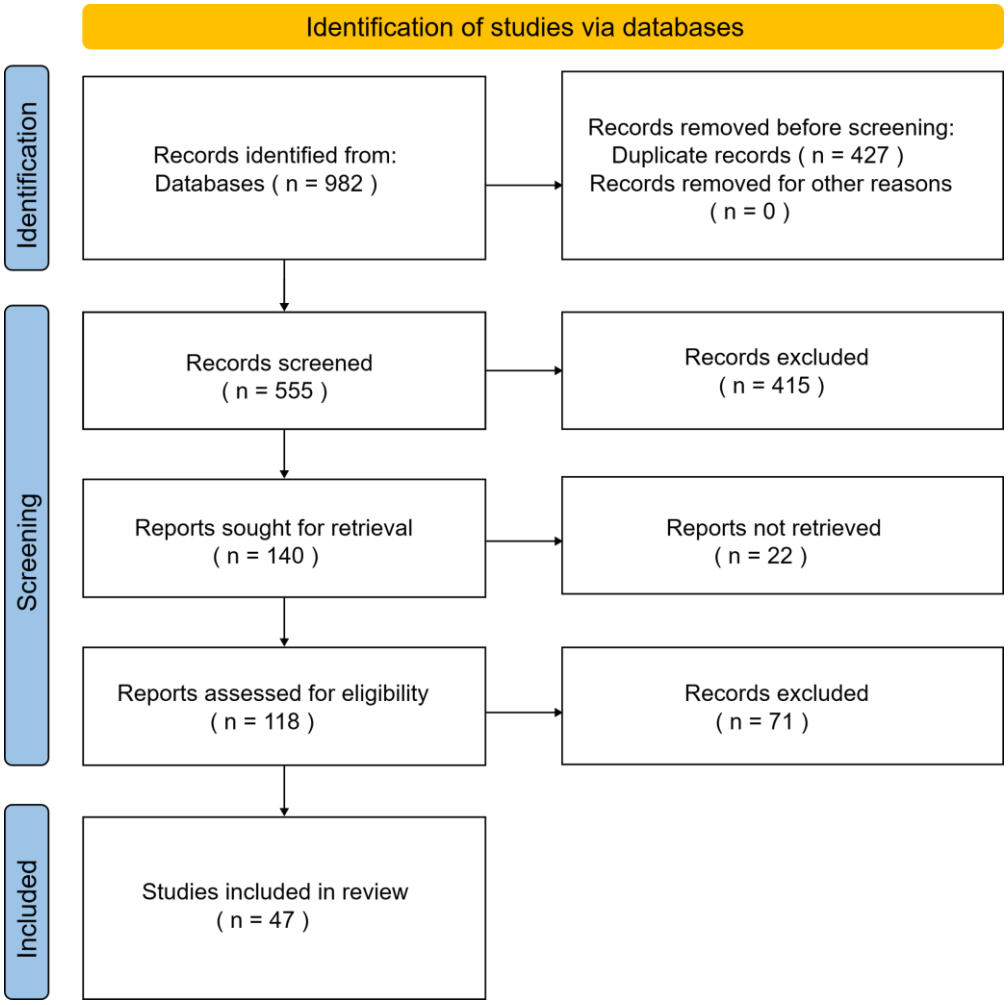


Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram of the study identification, screening, eligibility assessment, and inclusion process.

Quality appraisal was adapted to the design of the study. Experimental/field studies were evaluated with respect to instrumentation, monitoring period and season, uncertainty and representativeness. Model provenance and validation, boundary transparency and sensitivity analysis were assessed in the simulation studies. Economic studies were checked for tariff/discount assumptions and subsidies, as well as cost coverage. The ratings were used in the process of interpretation, rather than as a pooled score.

Language and access bias might be introduced due to review is limited to English-language work and full-texts are not available for all reviewed work. Results must also be considered in the context of the limited number of deployments, the variability of outcomes, and the different types of metrics used.

3. Results

3.1 Research Trends

The temporal evolution shows signs of recent growth, with previous research focusing on setting up basic monitoring and automation, and recent research incorporating IoT platforms, optimisation, and machine learning. The size of the corpus is still small compared to the literature on solar-pumping in general.

Following the increases in publication counts in 2016 and 2017, counts increased to four in 2018 and five in 2019, before a few fluctuations and a greater number of recent publications. It's a pattern that implies a developing research field (as opposed to an established one), and activity levels vary from year to year.

The timeline indicates that the demonstrations have moved from component to system integration and prediction. But the increasing publications in recent years have yet to be matched by increases in long-term field evidence.

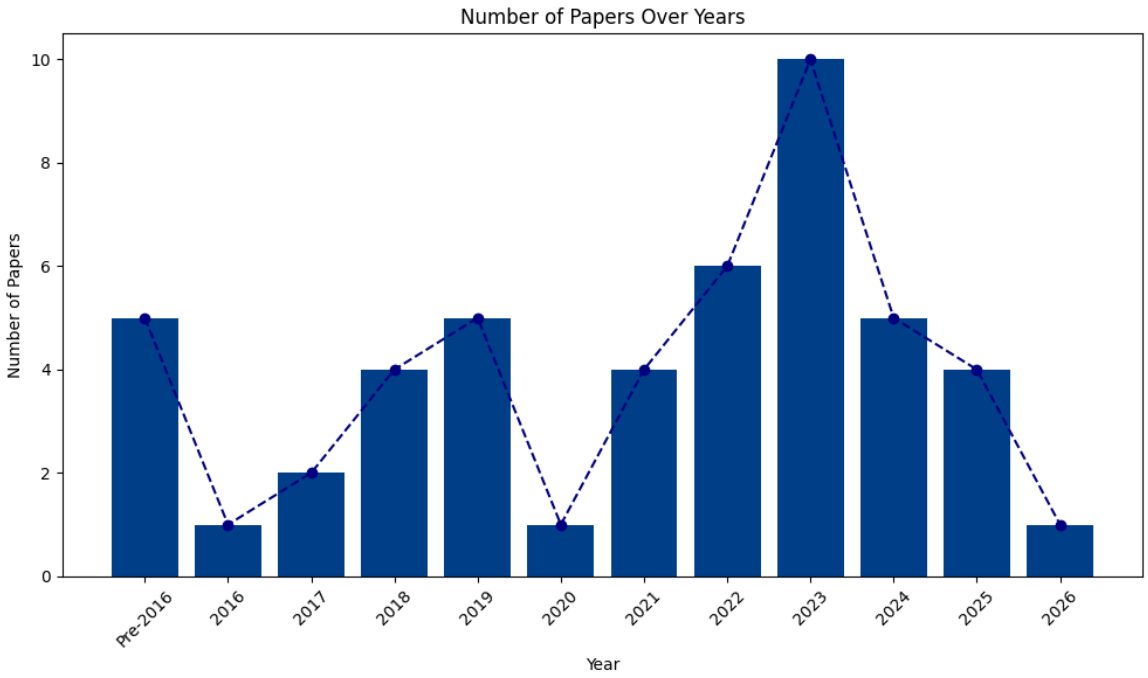


Figure 2. Temporal distribution of the 47 included studies on intelligent and Internet of Things (IoT)-enabled solar water pumping systems for off-grid water supply.

3.2 Report on included studies

A brief summary of representative architectures, intelligent functions and validation evidence is presented in Table 1, across the table themes. A detailed thematic tables summarising irrigation automation, IoT monitoring and predictive/adaptive control follow.

Table 1. Representative characteristics of included intelligent solar pumping studies

Study	System / intelligence	Primary function	Validation evidence
(Abdelkerim *et al.*, 2013)	supervisory control and data acquisition (SCADA)/programmable logic controller (PLC); soil-moisture sensors	Automated valve actuation	System design
(Cervera-Gascó *et al.*, 2023)	I-Selector scheduling model	photovoltaic (PV)-aware irrigation sequencing	Model evaluation
(García *et al.*, 2017)	Smart Photovoltaic Irrigation Manager	Energy–water scheduling	Seasonal orchard simulation
(Wanyama *et al.*, 2023)	Soil-moisture feedback; tank-level control	Automated irrigation scheduling	Field testing
(Ahmed & Iqbal, 2023)	Node-RED, mobile app, short message service (SMS)	Remote monitoring and control	Application evaluation
(Cervera-Gascó *et al.*, 2022)	artificial neural network (ANN)/Bayesian framework + genetic algorithms	PV power prediction	System validation
(Al-Obaidi & Derbel, 2023)	Internet of Things (IoT) data + convolutional neural network (CNN)	PV shading-fault detection	Simulation/classifier comparison
(Al-Obaidi *et al.*, 2024)	ANN with field sensor data	Fault detection/localization	Simulation compared with field data

There are variations in system size, design, control and validation among the studies. Thus Table 1 is not intended to be a direct indicator of performance ranking, but rather descriptive of the results of each study under the specific methods and conditions of each.

3.3 Automated Irrigation Management and Water Optimization

It seems that the biggest strand is automated irrigation management. Intelligence is mainly exploited for water-scheduling based on soil-moisture sensing, tank-level feedback, demand forecasts or PV-related water sequencing. Most implementations seem to be reactive, some coordinate water demand with availability of the sun.

Table 2. Representative automation and water-optimization strategies

Study	Inputs / logic	Actuation / function	Reported evidence
(Abdelkerim *et al*., 2013)	Soil-moisture sensors; supervisory control and data acquisition (SCADA)/programmable logic controller (PLC)	Two solenoid valves	Reactive moisture control
(Kholifah *et al*., 2019)	Soil humidity sensor	Drip irrigation pump	Trigger below 70% soil humidity
(Cervera-Gascó *et al*., 2023)	Photovoltaic (PV) availability and well capacity	Irrigation subunits	Energy-aware schedule
(García *et al*., 2017)	PV production and irrigation demand model	Irrigation sectors	Energy–water coordination
(Sheikh *et al*., 2018)	Weather sensors and an evapotranspiration (ET) model	Pump control	Proportional–integral–derivative (PID) scheduling; model-stage validation
(Wanyama *et al*., 2023)	Soil moisture and tank level	Pump/tank control	Field-tested feedback scheduling
(Dey *et al*., 2024)	Solar tracker and PV monitoring	PV-powered pump	26.72% output-power increase reported
(Setiawan *et al*., 2025)	Internet of Things (IoT) water-distribution robot	Water distribution	Water-distribution outcome not quantified in the cited source

Reactive threshold control seems to be widely used: the pump or valve is turned on/off if the moisture or tank level exceeds a predetermined threshold (Adeyemi *et al*., 2018). Although these can be cheap and easily understood, they require placement and calibration of the sensors and depend on the local conditions and do not predict the weather conditions or the need for the crop. (Schepen *et al*., 2024).

photovoltaic (PV)-aware scheduling further automates irrigation by matching the irrigation subunits to the PV energy supply and to the well capacity. Coordination of energy and water constraints, like in models such as I-Selector, is mostly on the model side and should not be confused with field demonstrated gains (Cervera-Gascó *et al*., 2023).

The optimisation of energy also plays a role in water delivery. To enhance the PV utilisation, solar tracking and maximum power point tracking (MPPT) have been considered, while optimisation-based controllers have been proposed to tackle the issues of partial shading and motor operation (Narvarte *et al*., 2018; Ouissaaden *et al*., 2026). These techniques may be used to improve the energy subsystem, although they do not necessarily show an improvement in irrigation results, unless water delivery is measured.

3.4 Internet of Things (IoT)-based real time monitoring and remote control systems

The IoT monitoring is about moving intelligence to sensing, communication and supervisory control. Common platforms include the use of cheap microcontrollers, electrical and water level sensors, wireless communication, and dashboards and remote control devices (Morchid *et al*., 2026). They aren't so much about decision making as they are about visibility and access.

Table 3. Representative IoT monitoring and remote-control architectures

Study	Platform / communication	Function	Validation
(Bukhari & Abdullah, 2022)	Arduino/Internet of Things (IoT) platform	Monitoring and fertigation	Prototype
(Jucá *et al*., 2015)	Wi-Fi data acquisition	photovoltaic (PV) pumping plant monitoring	System demonstration
(Ahmed & Iqbal, 2023)	Node-RED, MIT App Inventor, short message service (SMS)	Water-level display and remote commands	Application evaluation
(Chidolue & Iqbal, 2023)	PLX-DAQ over universal asynchronous receiver-transmitter (UART)	Voltage/current logging	Data-logging demonstration
(Mahjoubi *et al*., 2011)	Wireless acquisition; short message service (SMS)/Global System for Mobile Communications (GSM)	Remote multi-site monitoring	Communication alternatives assessed
(Chieochan *et al*., 2017)	IoT sensors; Blynk dashboard	Smart-farm monitoring	Case study

(Selmani *et al.*, 2018)	Vert.x client–server; cloud microservices	Remote greenhouse management	Experimental greenhouse case
(Rumbayan *et al.*, 2025)	Microcontroller and IoT monitoring	Rural domestic water supply	System integration study

There seem to be 3 patterns: low cost microcontroller is the most common, Wi-Fi, GSM/SMS and cloud dashboards are used for connectivity, and sensor suites focus on electrical variables, tank level and soil moisture. There is limited interoperability and consistency in data formats.

Interoperability and system-level architecture is considered by a smaller group. These studies seem to show the potential of client–server and cloud approaches and standards-based integration and maintainability is not always assessed (López-Morales *et al.*, 2020).

Validation appears uneven. Many monitoring systems are described as prototypes or demonstrations and not much information is provided on the reliability of the communications system, cybersecurity, maintenance or user uptake and performance across multiple seasons. Monitoring capacity does not necessarily translate into practical benefits.

3.5 Intelligent Predictive and Adaptive Control for Solar Pumping

Predictive and adaptive control is able to predict PV output, water demand or equipment status. While this strand is much smaller than reactive automation and monitoring, it seems to be the best indication of closed-loop intelligence.

Table 4. Intelligent predictive and adaptive control characteristics of the included studies

STUDY ID	INTELLIGENT CONTROL TECHNIQUE	MACHINE LEARNING / ARTIFICIAL INTELLIGENCE METHOD	CONTROL OBJECTIVE	VALIDATION APPROACH
(Cervera-Gascó *et al.*, 2022)	Power prediction up to 3 h ahead with Bayesian-framework artificial neural networks (ANNs) coupled to genetic algorithms (PREPOSOL)	Bayesian ANN + genetic algorithms	Photovoltaic (PV) power forecast for irrigation scheduling	Validated on a PV pumping system, Albacete, Spain; relative error 8.10% and R^2 = 0.9157
(García *et al.*, 2017)	Real-time Smart Photovoltaic Irrigation Manager (SPIM) synchronizing photovoltaic power availability with the pumping energy required by different irrigation sectors	PV, hydraulics and soil-water simulation	Meet irrigation demand; balance energy deficits with storage or extended irrigation events	Simulated Southern Spain olive orchard, 2013 season
(Al-Ali *et al.*, 2019)	Fuzzy logic-based control mode within a three-mode operating architecture	Fuzzy logic	Rule-based inference of actuation commands from soil moisture, humidity, temperature, and well level inputs	Prototype designed, built, and tested across local, mobile, and fuzzy modes
(Malla *et al.*, 2022)	Sensorless sliding mode controller (SMC) combined with a hybrid whale optimization–perturb-and-observe (WOPO) maximum power point tracking (MPPT) algorithm	Whale optimization algorithm, genetic algorithm, particle swarm optimization, and grey wolf optimization benchmarking	Global maximum power point tracking under partial shading with simultaneous speed regulation of the brushless direct-current (BLDC) pump motor	OPAL-RT real-time simulation under steady-state and transient conditions; dSPACE hardware validation

(Al-Obaidi & Derbel, 2023)	Convolutional neural network (CNN)-based fault detection and localisation using Internet of Things (IoT) data	CNN using electrical indicators as inputs	PV shading-fault detection/localisation	MATLAB; compared with statistical/ML classifiers
(Al-Obaidi *et al*., 2024)	ANN fault diagnosis with IoT data	Artificial neural network	Fault detection/classification/localisation	Simulation compared with field sensor data
(Ashik-E-Rabbani *et al*., 2026)	Machine-learning-driven automated irrigation decision-making across five solar-powered substations	Machine learning on capacitive soil moisture and DHT22 temperature–humidity data streams	Energy-aware and water-efficient automated irrigation scheduling	Development and evaluation of an AIoT architecture in water- and energy-constrained regions of Bangladesh

PV forecasting can be used to assist irrigation scheduling as it can help to know how much PV power is available before operation. The PREPOSOL approach is based on the fusion of BNN and GA; validation is done system-specific and generalisation to other climates and pump sizes is not guaranteed (Cervera-Gascó *et al*., 2022).
An alternative to machine learning forecasting can be using physics-based simulation, which can be done by linking PV production, hydrology and soil water balance. These types of models can be used to integrate irrigation and energy, although they require calibration, assumptions and field testing (García *et al*., 2017).
Fuzzy and optimisation-based controllers adjust the actuation with respect to several sensed variables. These can be expert rules or optimise motor/PV operation (Errouha *et al*., 2019), however, this is hard to compare when studies have different baseline, objective and validation levels.
Fault diagnosis by machine learning seems to be a new use, both convolutional neural network (CNN) and artificial neural network (ANN) methods rely on electrical and environmental data to detect or localise a fault, such as PV shading (Bougoffa *et al*., 2024; Li *et al*., 2020). Most evidence is still simulation-driven and/or based on small amounts of field data; reliable deployment is based on a variety of data sets and assessments in actual operating conditions.

4. Discussion

The evidence depicts a field with a lot of interest in connected and intelligent solar pumping, but not much on a durable benefit. The vast majority of systems seem to deliver reactive automation, or remote monitoring; predictive control and learning based adaptation are less prevalent and often not proven by long-term field operation.
The use of low-power microcontrollers might have reduced implementation hurdles and fueled the making of prototypes. But, interoperability, reliability or maintainability are not guaranteed through architectural similarity. Research should be more uniform in terms of component selection, communication failures, power consumption and failure handling.
Monitoring seems to be electrically oriented: voltage, current and PV-output are monitored more regularly than hydraulic performance, crop response, or delivered-water reliability. This imbalance restricts the statements that can be made about water-service outcomes and suggests the need for combined energy–water indicators.
The functional taxonomy seems to explain that monitoring, automation and predictive control are different levels of intelligence. Future studies need to be explicit about the use of forecasts and about the decision locus and autonomy of their use, and not just label them as ‘smart’ or ‘AI'.
Some of the limitations are that it only includes English language data, there may be some errors in the database, and the number of sustained field studies is small. For several reasons (heterogeneous system sizes, climates, metrics, and validation designs), conclusions are thematic and evidence weighted.
Top priority areas are standardised energy–water benchmarking, multi-season field trials, robust and interoperable architectures, cybersecurity and maintainability assessment, and predictive controllers tested in closed loop against transparent baselines. Costs, experiences and failure should be reported with the technical performance in studies.

5. Conclusion

This review compiled evidences regarding intelligent and IoT solar water pumping for off grid water supply. There is lack of field validation and predictive/adaptive control still seems to be a smaller strand in the literature,

compared to prototype monitoring and reactive automation. There are some reported benefits, but not yet consistent and comparable evidence for these benefits. The sensing, control and water-management goals should be co-designed and both energy and delivered-water results assessed. Common benchmarks, transparent baselines and long-term field trials should be used by researchers, while reliability, security, cost and user acceptance should be also considered by deployment decisions.

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