Verification Report

Large Power PV Water Pumping System

IN20180147UK03E

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Date	17 October 2019
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1. Introduction

1.1. Name of technology and unique identifier of the technology being verified

Name: Large Power PV Water Pumping System (LPPWPS)

Identifier: This verification is specific to the system control software that was in use during the data collection period for this verification (1 September 2017 to 31 August 2018), and the test system audit conducted on 6 November 2018 at the Comunidad General de Usuarios del Alto Vinalopó (CGUAV) [General Users Community of Alto Vinalopó (GUCAV)], Pozo San Cristóbal, Villena, Alicante, Spain.

Site Location: Longitude - 0° 50’ 32’’ West
Latitude - 38° 14’ 19’’ North
Altitude - 593m

1.2. Name and contact of proposer

Instituto de Energía Solar-Universidad Politécnica de Madrid (IES-UPM)
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1.3. Name of Verification Body and person responsible for verification

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1.4. Organisation of verification including experts, and verification process

Verification Body

BRE Global

Internal Expert: Dr John Holden (ETV), Nicolas Randall (ETV)
External Expert: Dr Colin Cunningham (EU ETV appointed expert)

Technology representatives

IES-UPM

Internal Experts: Luis Narvarte Fernandéz, Isaac Carrêlo, Francisco Martínez

DOMUS Ingeniería Energética

Technology installer: Alberto González

Comunidad General de Usuarios del Alto Vinalopó (CGUAV)
[General Users Community of Alto Vinalopó (GUCAV)]

Community user: Ismael Gil

Verification of the Large Power PV Water Pumping System (LPPWPS) was carried out in accordance with GVP 1.3. The verification consisted of an on-site inspection to confirm the test site configuration including siting of data collection instruments, and subsequent review of test data from the inspected site.

1.5. Deviations from the specific verification protocol (SVP)

The site selected by the proposer is powered solely by solar photovoltaics and pumps water to a reservoir. Hence IES-UPM agreed that the focus of the verification should be the passing cloud algorithm which enables the system to be powered solely by solar photovoltaics. It was also agreed that, in order to perform this assessment, data obtained for a period of 12 consecutive months beginning 1 September 2017 would be analysed and the acceptability of the permanent on-site measurement equipment/dataloggers (regarding location, suitability, calibration) to record these data would be assessed. Consequently, data collection from further testing was not required.

Since the system is specifically designed to work with the passing cloud algorithm it was not possible to switch the passing cloud algorithm off in order to obtain comparable performance data. This was considered ok.

Furthermore, it was agreed that reduced water consumption would not be assessed at this location because the water is pumped to a reservoir of approximately 173,000m^3 for communal use which is not controlled by the LPPWPS.

Figure 1 – Reservoir at Villena, approximately 173,000m^3

2. Description of the technology and application

2.1. Summary description of the technology

The LPPWPS technology is a control system for large-scale irrigation powered solely by solar photovoltaics (PV) with no alternative power source such as grid connection, battery storage, or back-up generator. The control system incorporates an innovative ‘Passing Cloud’ algorithm that assesses a number of system parameters in order to identify passing clouds. When a passing cloud is identified the system implements a special set of operating instructions to overcome the sudden drop in PV array power output (caused by the momentary shading of the PV array) and avoid abrupt pump shutdown.

By doing this the LPPWPS technology reduces the risk of damage to the pumping system from hydraulic shock (e.g. due to water hammer) and to the electrical system due to sudden power fluctuations (overvoltage, surge current.)

The LPPWPS in Villena is configured in the following way:

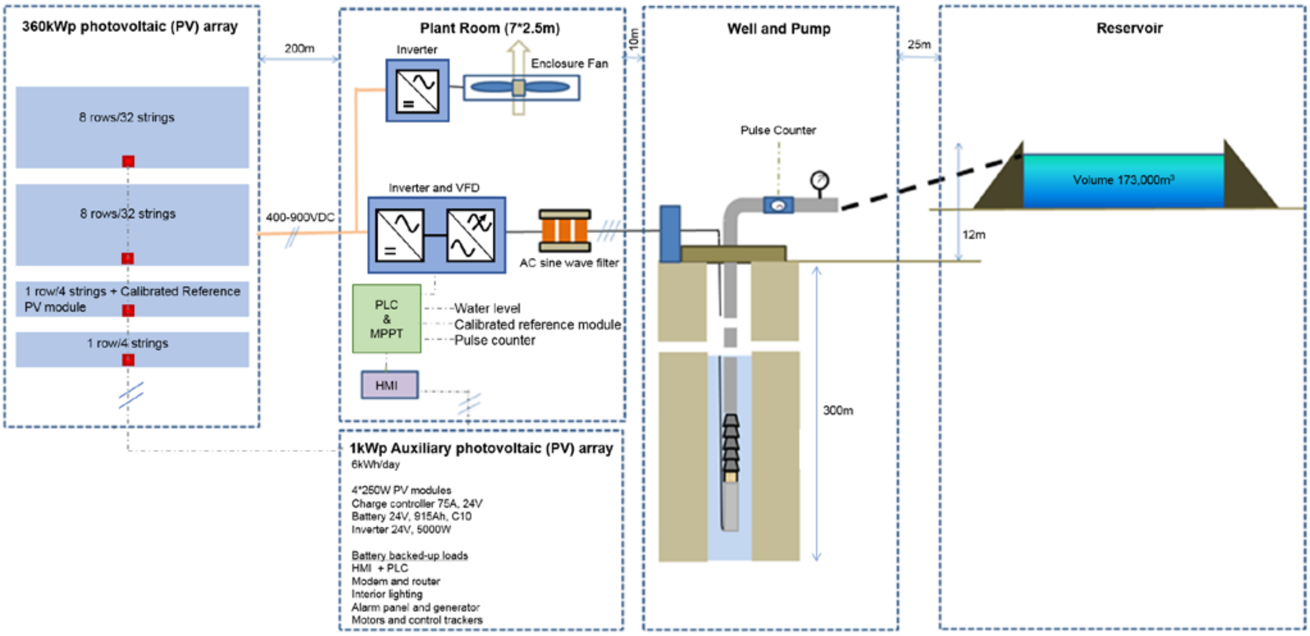


Figure 2 – System configuration at Villena

System Components:

Solar Photovoltaic (PV) array – 360kWp (at Standard Test Conditions (STC) as described in BS EN 61215-1:2016)

Calibrated Reference PV module – this single module provides irradiance and cell temperature data to the PLC.

Programmable Logic Controller (PLC) – is programmed with site specific data to provide control of the system.

Proportional–Integral–Derivative (PID) controller – maintains system performance by analysing system data and making appropriate corrections.

Maximum-Power Point Tracking (MPPT) – optimizes the power output of the PV array.

Variable Frequency Drive (VFD) – varies the frequency and voltage of electricity supplied to the pump to match its power consumption with that available from the PV system.

AC Sine wave filter – improves the quality of power delivered from the VFD to the pump motor.

Water Pump – 250kW submersible vertical electro-pump which pumps water from the well to the reservoir.

Algorithms:

- **Passing Cloud Algorithm** – analyses system performance and identifies transient power drops i.e. passing clouds.
- **Start-Up Algorithm** – starts the pump when the estimated PV power is >160kW and the frequency of the output from the VFD is >38Hz for more than 60 seconds.
- **Stop Algorithm** – performs a controlled shutdown of the pumping system by ramping down the power to the pump when the estimated PV power is <130kW or the frequency of the output from the VFD is <38Hz for more than 60 seconds.

The photovoltaic (PV) system has a nominal generating capacity of 360kWp (at STC). The PV array consists of 1,440 modules with a rated Maximum Power (P_{max} at STC) of 250W per module. The PV array has 72 rows connected in parallel. Each row has 20 PV modules connected in series. The PV array is mounted on 18 North-South horizontal axis trackers. Each tracker has 4 rows of 20 PV modules in series. The calibrated reference PV module is affixed to one of the rows therefore tracks the orientation of the PV array.

Figure 3 – Photovoltaic (PV) array at Villena, 360kWp

How the Large Power PV Water Pumping System works

The system uses irradiance and cell temperature data from the calibrated reference PV module to estimate the power generated by the PV array. A check is made on whether the pump is running or not and what the estimated PV power is. Depending on the answers the system will start, stop, or continue in its current mode. The MPPT optimises the PV power output and the PID makes corrections to optimise overall system performance such as correcting/adjusting the output to the pump, via the VFD, to keep the DC bus voltage above the critical threshold of 500VDC to prevent system shutdown and consequently pump shutdown.

The flowchart below details the system logic.

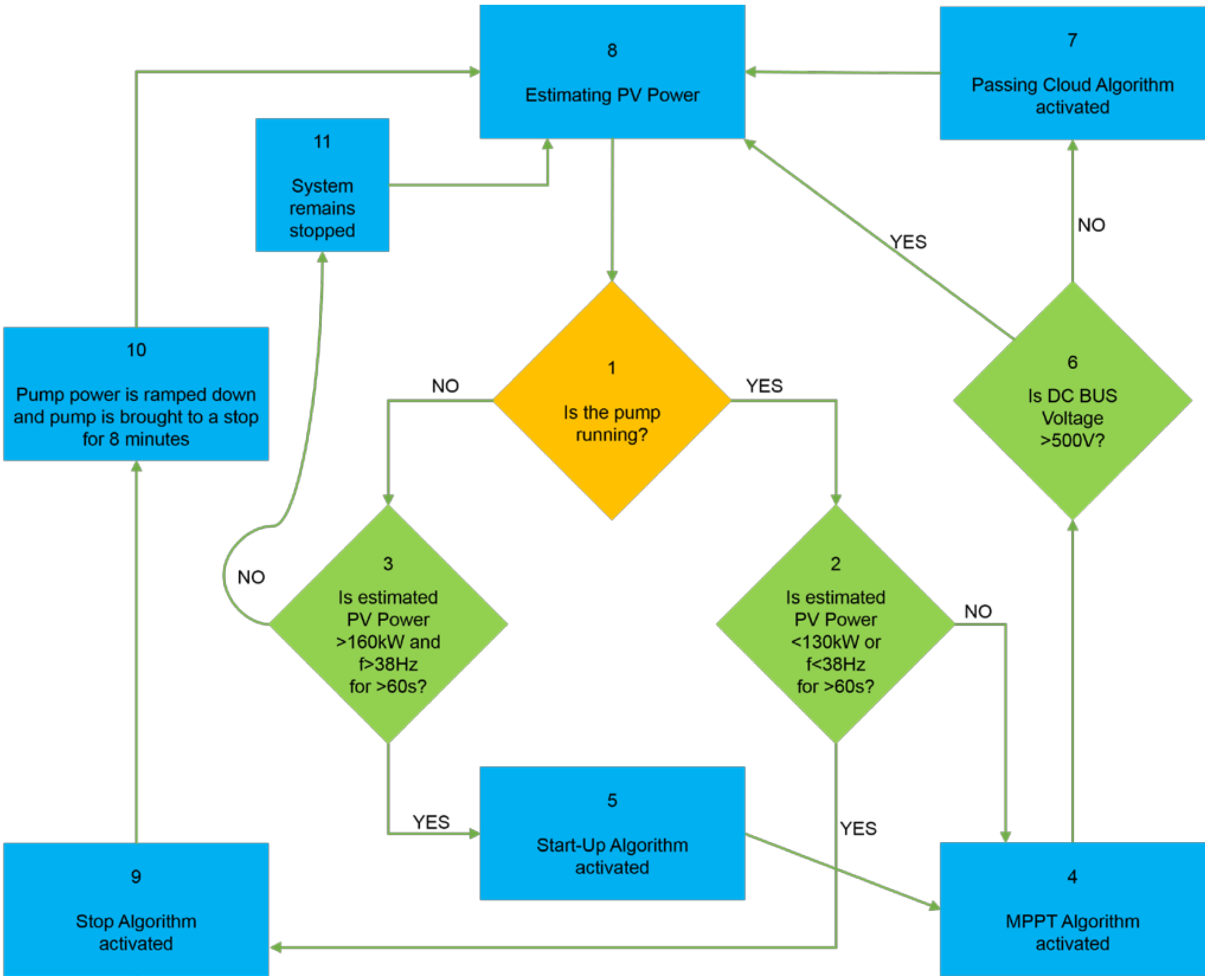


Figure 4 - Control System flowchart

How the Passing Cloud Algorithm works

The Passing Cloud algorithm works by taking irradiance data from the calibrated reference PV module and comparing it against a set of site-specific values that represent the critical limits for uninterrupted operation of the pump during 60 second periods when the PV power output decreases due to shading of the PV array caused by a passing cloud. When specific criteria are met the Passing Cloud algorithm is activated and overrides the PID to allow it to make voltage and frequency corrections to the pump via the VFD, corrections that the PID is not programmed to make.

Reducing the voltage and frequency to the pump increases the DC bus voltage which helps to maintain it above the critical threshold of 500VDC. With the DC bus voltage kept above 500VDC the system continues to operate uninterrupted.

Passing Cloud criteria:

$G_{t0}>G_{min}$

$G_{t1}<dG_{t0}$

$G_{t3}\geq aG_{t0}$

Where:

- G = measured irradiance (W/m2)
- G_{min} = 400W/m2 (specific to Villena site)
- $_{t0}$ = 0-20 seconds
- $_{t1}$ = 21-40 seconds
- $_{t2}$ = 41-60 seconds
- $_{t3}$ = 61-80 seconds
- d = descent coefficient (0.5)
- a = ascent coefficient (0.8)

Passing cloud definition:

- The pump is running (i.e. ‘RUN = 1’)
- The estimated PV power is >130kW and VFD frequency >38Hz for a period of >60s.
- During G_{t0} the irradiance is $>G_{min}$ (e.g. 800W/m^2).
- During G_{t1} the irradiance decreases to $<0.5G_{t0}$ (e.g. 300W/m^2).
- During G_{t3} the irradiance increases to $\geq 0.8G_{t0}$ (e.g. 700W/m^2).

The different sequences of the Control System Flowchart (*Figure 4*), including the Passing Cloud algorithm permutations, are given in the following 5 scenarios:

Scenario A: No cloud detected

The pump is running and parameters are sufficient for uninterrupted operation. There is either no cloud or not enough cloud to cause irradiance to fall below the threshold.

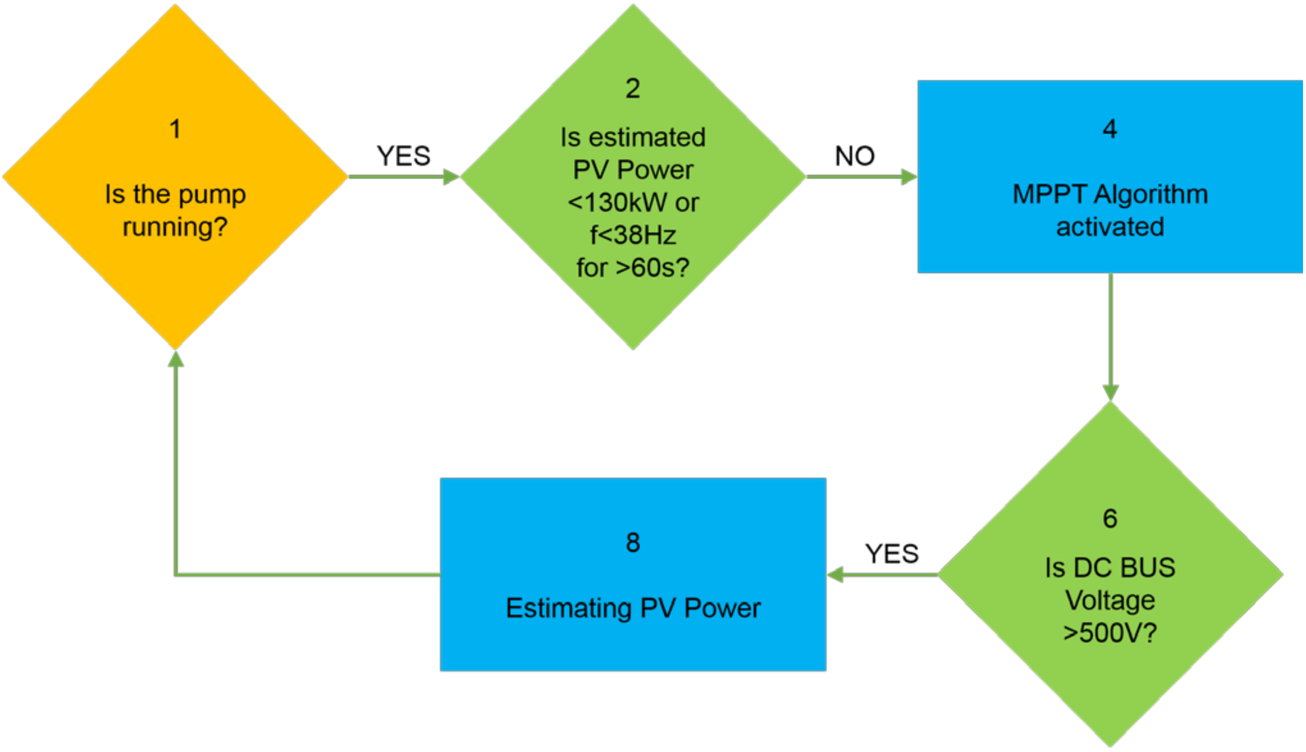


Figure 5 – No cloud detected flowchart

Figure 6 - No cloud detected graph

Scenario B: Passing cloud detected and avoided

The pump is running when a passing cloud momentarily shades the PV array causing the PV power output to fall suddenly. The PID cannot maintain the DC bus voltage above the threshold so the Passing Cloud algorithm is activated and the PID controller is deactivated. The Passing Cloud algorithm reduces the voltage and frequency to the pump via the VFD which causes the DC bus voltage to increase. The DC bus voltage is maintained above the threshold and the pump is kept running as the cloud passes within 60 seconds.

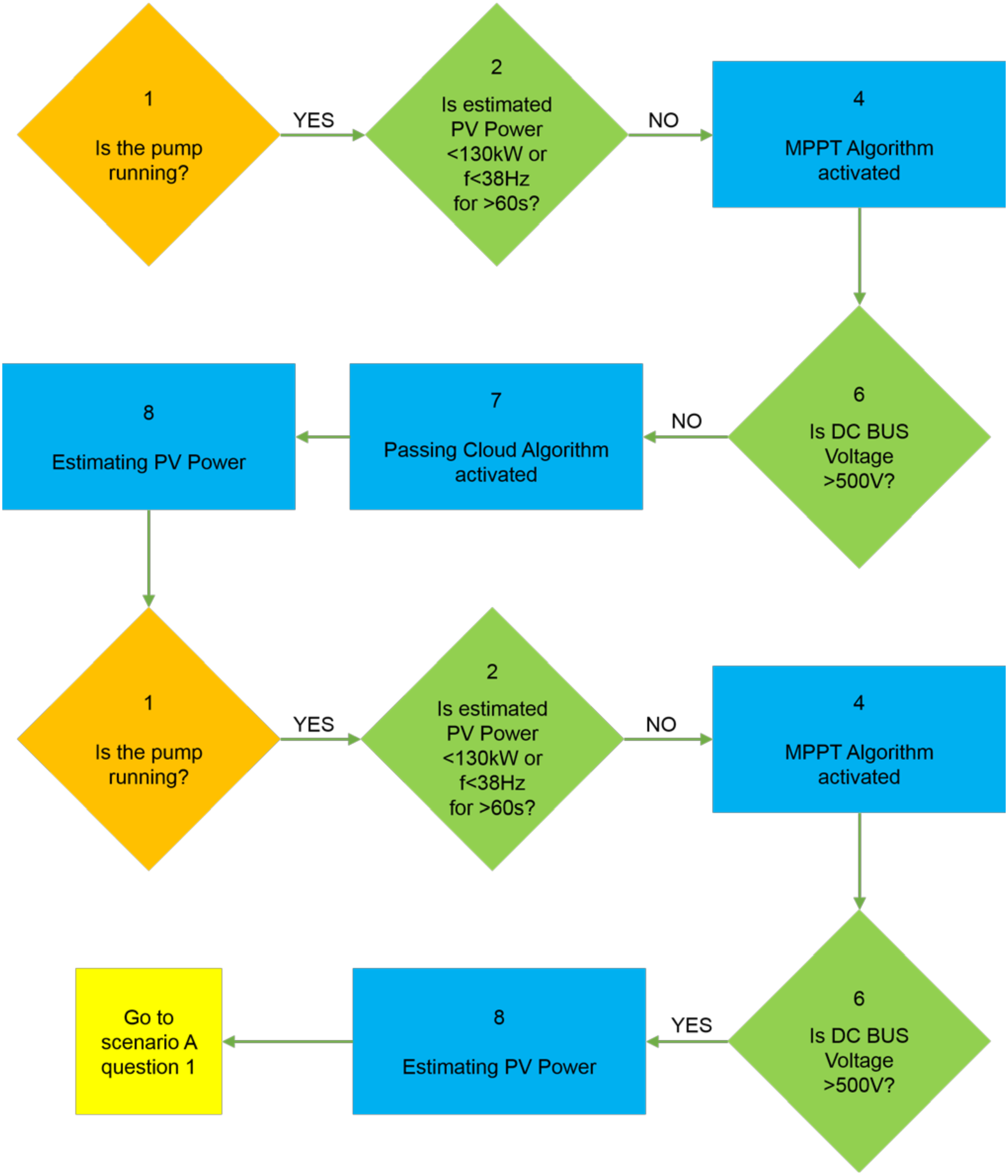


Figure 7 – Passing cloud detected and avoided flowchart

Figure 8 - Passing cloud detected and avoided graph

Scenario C: Persistent cloud detected

The pump is running when cloud shades the PV array causing the PV power output to fall suddenly. The PID cannot maintain the DC bus voltage above the threshold so the Passing Cloud algorithm is activated and the PID controller is deactivated. However, the cloud persists and irradiance does not increase sufficiently during the 60 second time frame. The Passing Cloud algorithm is unable to decrease the voltage and frequency via the VFD to the pump any further to maintain the DC bus voltage. Therefore, the Stop algorithm is activated. The power to the pump is ramped down and the system undergoes a controlled shutdown. Restart is prevented for at least 8 minutes.

n.b. This may also occur due to very low light levels. Either way, the required power and/or frequency cannot be maintained by the PID controller or Passing Cloud algorithm.

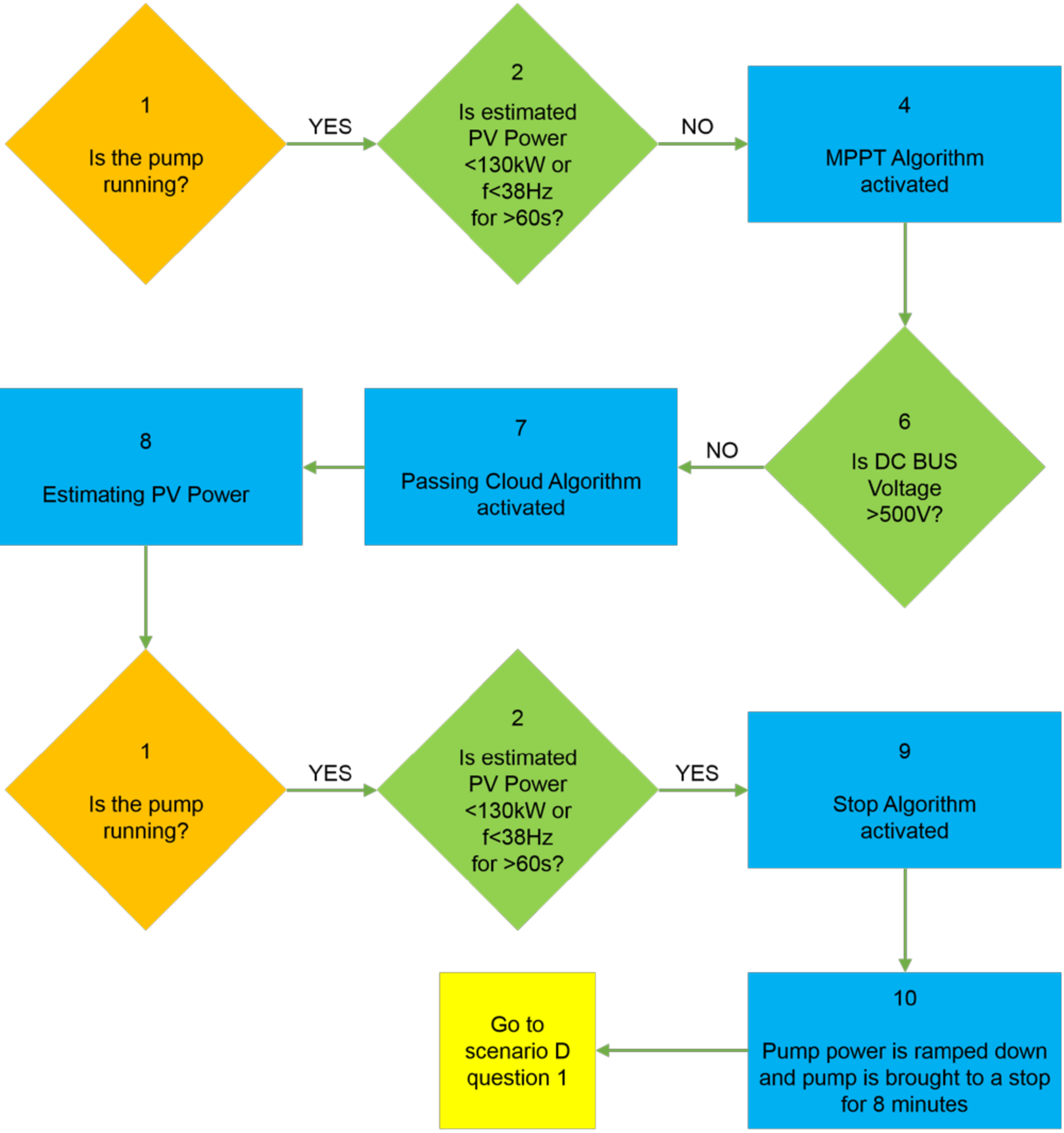


Figure 9 - Persistent cloud detected flowchart

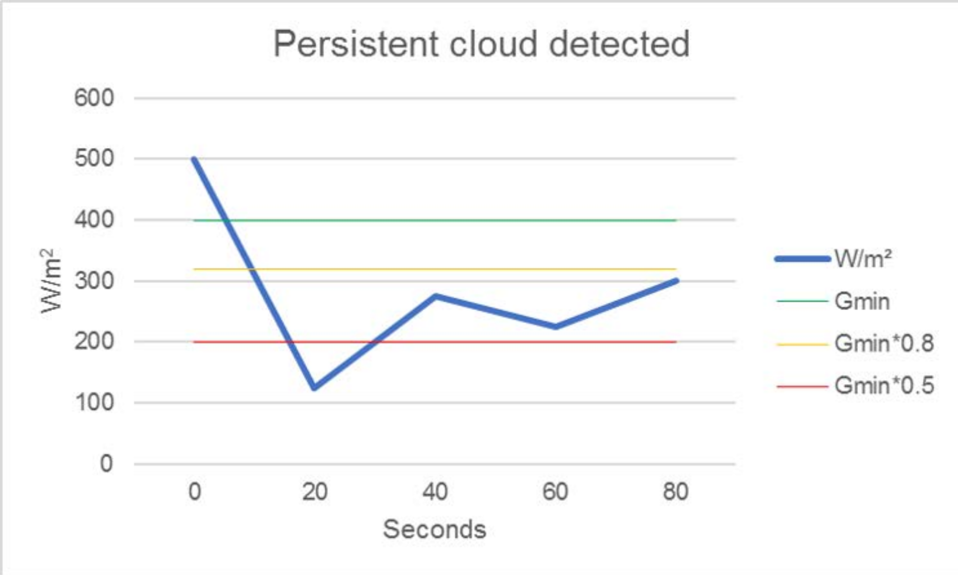


Figure 10 - Persistent cloud detected graph

Scenario D: System restart

At least 8 minutes have elapsed since the system was stopped. The pump is not running, the estimated PV power is >160kW and the VFD frequency is >38Hz for >60s so the Start-Up algorithm is activated. When the system logic returns to question 1 and the answer is 'YES' i.e. the pump is running, then scenario A will be in effect.

n.b. If the system had been shut down (e.g. due to a persistent cloud as in scenario C) and prevented from restarting for 8 mins, then the 8-minute safety period must expire before a system restart can be activated.

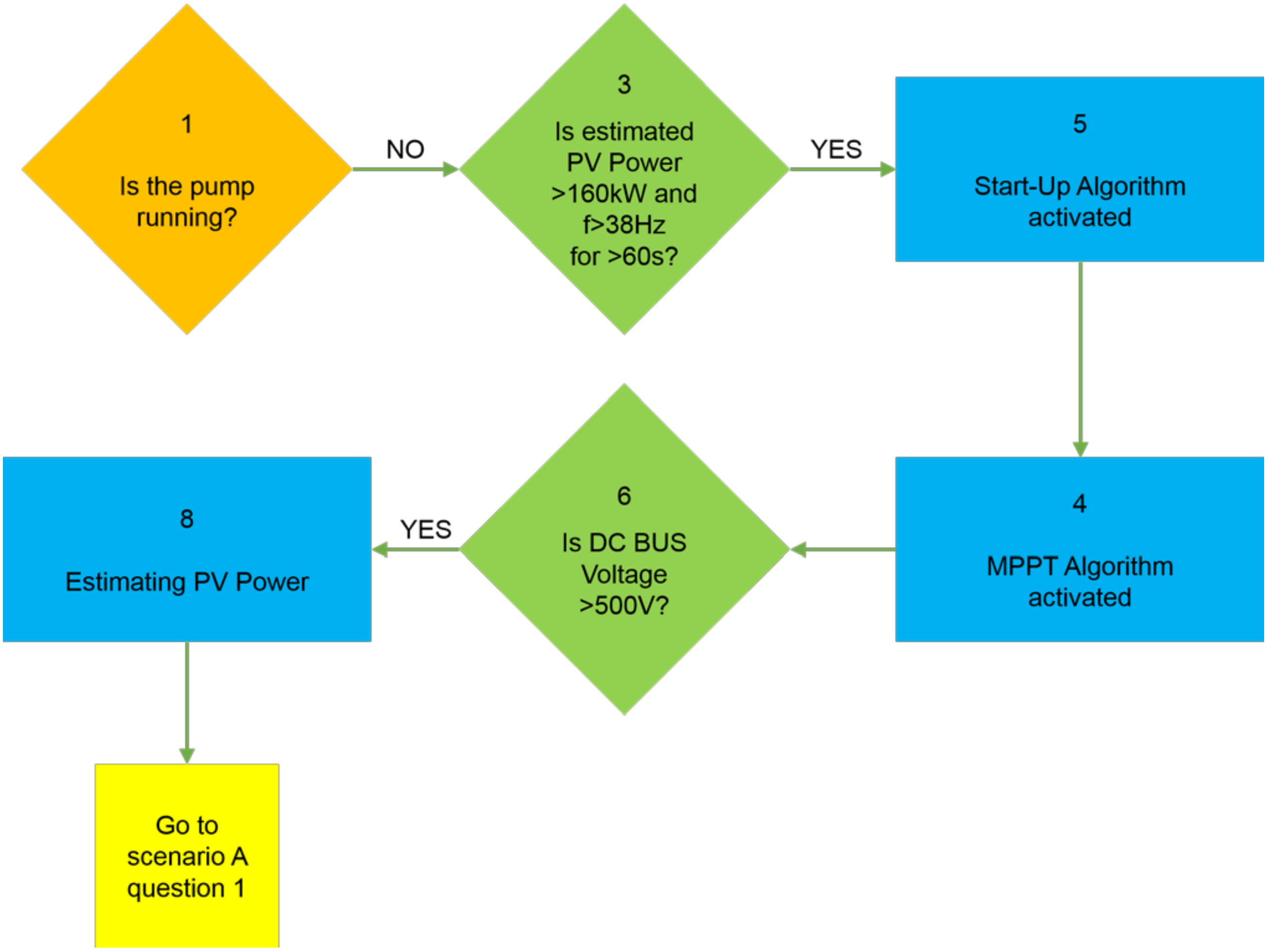


Figure 11 - System restart flowchart

Scenario E: System stopped

The pump is not running, and the estimated PV power is <160kW and/or the frequency is <38Hz for >60s. The system remains stopped.

n.b. When the estimated PV power is >160kW and the frequency is >38Hz for >60s then scenario D will be in effect.

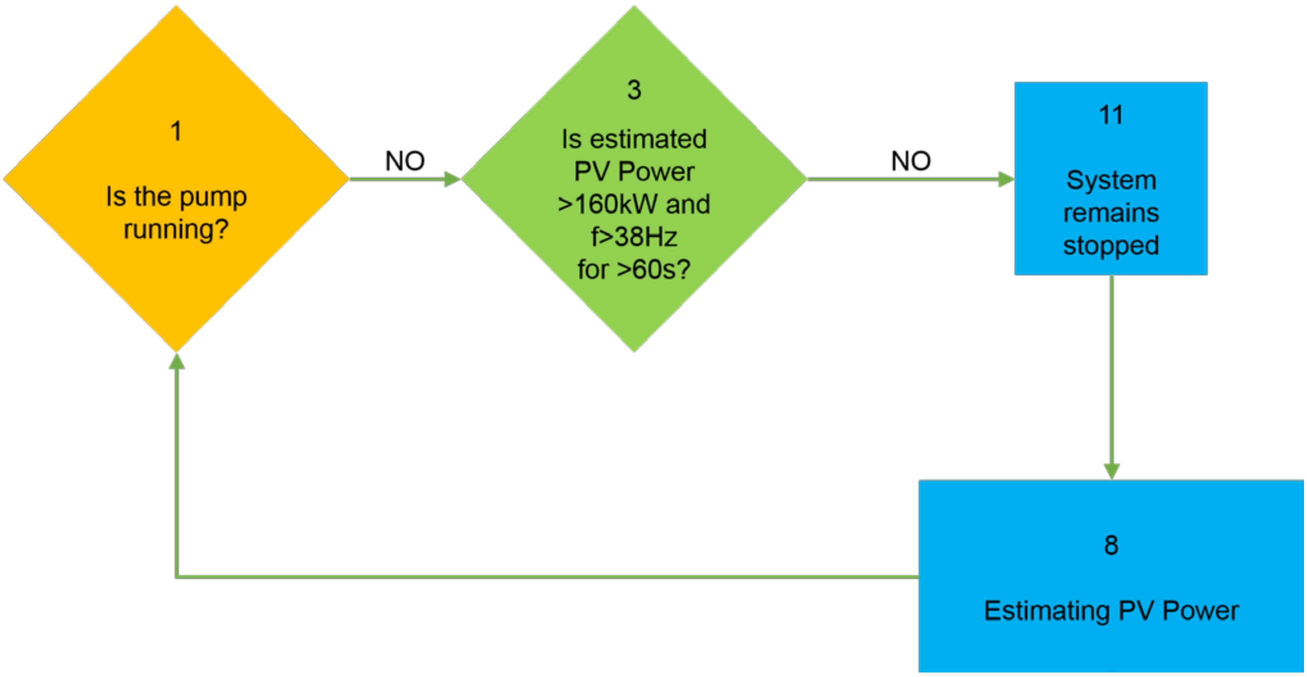
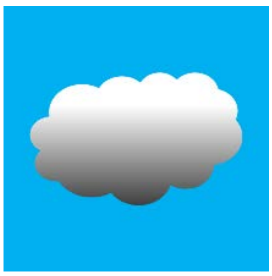


Figure 12 - System stopped flowchart

OR



2.2. Intended application (matrix, purpose, technologies, technical conditions)

Matrix: Large scale solar photovoltaic (PV) powered pumping and irrigation systems

Purpose: Facilitate the use of solar PV as the sole means of powering large scale pumping and irrigation by reducing the risk of system damage caused by abrupt pump shutdown which may occur due to transient PV power drops caused by intermittent shading of the PV array (e.g. by passing clouds).

Technologies: Solar Photovoltaics, irrigation, Programmable Logic Controllers (PLC), Proportional–Integral–Derivative (PID) controllers, Variable Frequency Drives (VFD).

Technical conditions: The PLC, including all algorithms, and PID must be correctly programmed for the specific site. The solar photovoltaic array must be correctly designed to meet the power requirements of the pumping system. Sufficient water resource must be available. Equipment must be installed, operated and maintained in accordance with manufacturer's instructions.

2.3. Verification parameters definition

Performance parameters:

- The Passing Cloud algorithm is ≥95% efficient
  - Number of passing clouds detected
  - Number of passing clouds avoided

Operational parameters:

- Irradiance ≥400W/m^2
- Estimated PV power >130kW
- VFD output frequency >38Hz
- VFD DC bus voltage >500DCV
- 20 second data collection frequency

Environmental parameters:

- The water pumping system is powered solely by solar photovoltaics

Additional parameters:

- The LPPWPS has a ROI of approximately 8 years. This does not include the irrigation systems that are fed from the reservoir.

3. Existing data

3.1. Accepted existing data

Data collected from the Villena site between 1 September 2017 and 31 August 2018 were accepted for this verification. These data were provided in Excel spreadsheets. It was confirmed that all necessary equipment had valid calibration certificates for this period.

4. Evaluation

4.1. Calculation of verification parameters including determination of uncertainty

The effectiveness of the Passing Cloud algorithm is calculated using an Excel formula based on the Passing Cloud algorithm. The Excel formula uses irradiance and pump data to determine when the criteria for a passing cloud (i.e. one that **doesn't** cause pump shutdown) and a persistent cloud (i.e. one that **does** cause pump shutdown) have been met and records the outcome.

The accuracy of the irradiance data is dependent on the calibrated reference PV module. The calibrated reference PV module was subjected to four stages of calibration in order to determine a standard deviation of 0.67%.

Calibration procedures carried out by different laboratories. Likewise, the initial calibration values are also shown with their respective uncertainties (k = 1) and corrected for temperature, angle and AM.

Independent calibrations						
Date	Calibration body	Initial calibration		Procedure	Corrected calibration	
		Value (mV/(kW/m²))	Standard deviation (%)		Value (mV/(kW/m²))	Standard deviation (%)
March 2013	FISE	92.025	2	At a solar simulator against a reference cell	92.025	2
July 2014	CIEMAT	90.4	1	At natural sunlight against the global irradiance given by a pyranometer	90.354	1.459
May 2015	5th international spectro – and broadband radiometer intercomparison	90.84	0.87	At natural sunlight against the global irradiance given by a cavity pyrheliometer and a shaded pyranometer	90.796	0.988
February 2017	IES-UPM	91.384	1.05	At natural sunlight against a reference cell calibrated by NREL	91.089	1.445
March 2017	Final assigned calibration				90.899	0.67

Figure 13 – calibration stages of reference PV module

The pump data is binary and records whether the pump is running i.e. RUN = 0 (stopped) or 1 (running).

Ultimately, the accuracy of the irradiance and pump run data are secondary in the verification which focusses primarily on the Passing Cloud algorithm's effectiveness in interpreting whichever data are received and keeping the pump running. A 0% uncertainty is assumed for the ability of the Excel formula to execute the required calculations.

The PLC determines when the operational criteria are met and the pump should start/continue to run. These criteria are:

- At least 8 minutes since pump was stopped
- Irradiance ≥400W/m^2 for >60s
- Estimated PV power >160kW for >60s
- VFD output frequency >38Hz for >60s
- VFD DC bus voltage >500DCV

The data provided by IES-UPM indicate there are instances where the status of the pumping system (i.e. RUN = 1 or RUN = 0) appeared to be contrary to the operational criteria and associated system data. Such anomalies may occur under the following conditions:

(A) The first is when the system is restarting after a controlled shutdown. Data recording from the various loggers is sequential and takes 20 seconds to complete for all parameters. Hence, although all requirements for restarting the system may have been met, the monitoring system can take up to two cycles (i.e. 40s) to establish this. This can lead to situations where the system is not running when the system data indicate it should be.

(B) The second is when system data show the pump is running (i.e. RUN = 1) though the operational criteria required for this do not appear to have been met. Again, this is because data are recorded over a 20 second cycle. Such situations occur when the system is stopped at the beginning of a data collection cycle and the VFD output frequency is recorded as 0Hz. The system then starts the pump (i.e. RUN = 1) during the data collection cycle and non-zero DC current data are recorded. These data indicate the system is running – contrary to the indication from the VFD output frequency.

These situations are known to IES-UPM and work is planned to reduce the time taken for each data collection cycle so that the likelihood of such situations occurring are minimised.

4.2. Evaluation of test quality

Additional testing was not performed for this verification. BRE Global Limited conducted a test system audit of the LPPWPS used to generate the existing test data. During this audit the measurement equipment and data logger's calibration status were verified providing reassurance of data quality. The LPPWPS monitoring system data incorporates alarm flags for elements such as; well depth, overcurrent, undervoltage, irradiance/frequency, leakage current and pump motor temperature to alert the operator to a fault that could affect system performance and integrity. If an alarm is triggered this is represented by a '1' in the relevant system data.

4.2.1. Control data

There are no control data (i.e. pumping system data obtained when the passing cloud algorithm is deactivated) available from the Villena site as the site cannot be operated with the algorithm deactivated.

4.2.2. Audits

A test system audit was carried out on 6 November 2018 at the Villena site. The audit included assessment of system operation and components, such as, PV array and the calibrated control module, data loggers, plant room monitoring and control equipment. IES-UPM confirmed that the system has not been altered in any way since being commissioned up until the date of the audit. Therefore, the system inspected was the same as that which generated the data used for this verification.

4.3. Verification results (verified performance claim)

The 250kW submersible vertical electro-pump of the Large Power PV Water Pumping System (LPPWPS) situated in Villena, Spain, is powered solely by the 360kWp integrated/on-site solar photovoltaic system.

Over a period of 12 months, from 1 September 2017 to 31 August 2018, the patented Passing Cloud algorithm prevented pump shutdown on 494 out of 517 occasions where the passing cloud criteria were met.

This indicates the passing cloud algorithm was 95.6% efficient.

$$\frac{494\ Passing\ Clouds\ Resisted}{517\ Passing\ Clouds\ detected} = 95.6\%\ efficient$$

4.3.1. Description of statistical methods used

Data for the 12-month period were provided in Excel format. BRE Global Limited applied an Excel formula that replicated the algorithm. Examples of the 'passing cloud' formulae are shown below:

Passing Cloud detected: =IFERROR(IF(AND(Z2=1,I2>400,I3<0.5*I2,I5>=0.8*I2),1,0),0)

Passing Cloud avoided: =IF(AND(AH2=1,Z5=1),1,0)

<u>Excel formula for Passing Cloud algorithm</u>

Row data	Excel formula	Data field	Data field description	Data	Criteria
Passing Cloud detected					
G_{t0}	Z2=1	RUN	Is the pump running in G_{t0}?	0 or 1	RUN must equal 1 to trigger the passing Cloud algorithm.
G_{t0}	I2>400	Irradiance	Is the irradiance on the control module greater than 400W/m^2?	W/m^2	Irradiance must be ≥G_{min} (i.e. 400W/m^2) in G_{t0} to fit the algorithm.
G_{t1}	I3<0.5*I2	Irradiance	Is the irradiance on the control module less than 50% of its value in G_{t0}?	W/m^2	Irradiance must be <0.5G_{t0} in G_{t1} to fit the algorithm.
G_{t3}	I5>=0.8*I2	Irradiance	Is the irradiance on the control module greater than 80% if its value in G_{t0}?	W/m^2	Irradiance must be ≥0.8G_{t0} in G_{t3} to fit the algorithm.
Passing Cloud avoided					
G_{t0}	AH2=1	Passing Cloud detected	Has a passing cloud been detected?	0 or 1	Passing Cloud detected must equal 1 having been detected in accordance with the criteria above.
G_{t3}	Z5=1	RUN	Is the pump running in G_{t3}?	0 or 1	RUN must equal 1 in G_{t3} to confirm that the algorithm prevented the pump from shutting down.

Table 1

4.3.2. Verification parameters

Performance parameters

Effectiveness of Passing Cloud algorithm

Excel formulae that replicate the Passing Cloud algorithms were written by BRE Global Limited in order to assess the data provided by IES-UPM and verify their figures for passing clouds detected and avoided.

Passing clouds detected/avoided/not avoided

Month/Year	Passing clouds detected	Passing clouds avoided	Passing clouds not avoided
September 2017	31	30	1
October 2017	28	27	1
November 2017	14	13	1
December 2017	17	16	1
January 2018	2	2	0
February 2018	18	17	1
March 2018	93	82	11
April 2018	96	92	4
May 2018	90	90	0
June 2018	49	47	2
July 2018	20	20	0
August 2018	59	58	1
Total	**517**	**494**	**23**

Table 2

Operational parameters

Installed solar PV capacity - the pumping requirements i.e. volume of water to be pumped (e.g. l/s), well depth, etc. established by IES-UPM indicated that a 360kWp solar PV array would generate sufficient electrical energy to power the LPPWPS. This was subsequently installed at the Villena site. To maximise electrical energy generation each of the 1,440 PV modules is mounted on a North-South horizontal axis tracker.

Global/in-plane irradiance - measured at the calibrated PV reference module and used in the estimation of PV generation.

Solar PV cell temperature - measured at the calibrated PV reference module and used in the estimation of PV generation.

Estimated PV power generation – determined using the equation:

$$PM = PM^{*}\left(1 + \gamma(TC - TC^{*})\right)$$

Where: PM^{*} is the nominal power of the PV generator at standard test conditions[1]

γ is the temperature coefficient of the PV module

TC is the cell temperature of the calibrated PV reference module

TC^{*} is the PV module cell temperature at standard test conditions[1]

The estimated PV power generation is used to determine if the system should start, stop, or continue in its current mode.

The estimated PV power generation must be >160kW for the system's Start algorithm to be activated. When the estimated PV power generation is <130kW the Stop algorithm will be activated.

Environmental parameters

During the site visit we confirmed that the pumping system is powered solely by the electricity generated by the 360kWp solar photovoltaic array.

Additional parameters

The ROI was not calculated or verified as part of this assessment.

5. Quality assurance

This verification was conducted according to the documented procedures of BRE Global Limited. These procedures fall within the scope of BRE Global Limited's Schedule of Accreditation to ISO/IEC 17020:2012 issued by the United Kingdom Accreditation Service (UKAS) and which includes internal and external review.

[1] Standard Test Conditions (STC) as described in BS EN 61215-1:2016