Final Report:

Pilot project To Trial
Solar F2D2

30 April 2021

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Lead Organisation

University of Queensland (UQ)

Industry Partner

Weidmuller Australia

Date

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Glossary

- Solar F2D2: Solar Farm Fault Detection and Diagnosis
- UQ: University of Queensland
- RDM: UQ's Research Data Manager
- O&M: Operations and Management

Acknowledgements

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I. Executive Summary

There was a manyfold increase in the number of large-scale solar farm installations in Australia between 2017 to 2019, increasing from 382 MW in 2017 to over 2.8 GW in 2019. The growth is likely to continue during the next decade. According to the Australian Energy Market Operator, 20 GW of new large-scale solar generation is currently proposed, part of which is expected to replace 13 GW coal fired generators that are due to retire by 2035. Much of this growth is attributed to solar farms with capacities greater than 50 MW. Each of the existing and upcoming solar farms are spread over hundreds of hectares of land and comprise hundreds of thousands of solar panels. The major challenge in managing these facilities is how to automatically diagnose underperforming panels in order to ensure maximum efficiency of power generation and reliability of assets. Whilst the scale and number of solar farms have grown exponentially, the underlying methods for condition monitoring and diagnostics in solar farms continue to be rudimentary. Economical, effective and efficient tools are urgently needed to meet the monitoring and management of the solar farms that are growing at an unprecedented rate.

The purpose of this project was to pilot trial our newly developed solar farm reliability enhancement tool named as 'Solar F2D2' – which stands for 'Solar Farm Fault Detection and Diagnosis'. It is essentially an all-in-one package that automatically detects and locates any faulty/underperforming panels and predicts panel soiling levels so that cleaning can be efficiently scheduled. The pilot trial was performed on a section of University of Queensland's Gatton Solar Research Facility. The specific objective of the trial was to evaluate performance and technical feasibility of Solar F2D2 in diagnosing underperformance in solar farms using the monitoring data available at solar farms as well as to estimate the additional economic value that can be derived through the use of Solar F2D2.

The project demonstrated the effectiveness of Solar F2D2 by quantifying the array specific underperformance levels in Gatton Solar Farm. Using the standard array level measurements and the available meteorological data, Solar F2D2 estimated array specific soiling levels and provided information about the number of underperforming strings and panels within each array. Solar F2D2 revealed that 5-10% of power production was reduced at Gatton farm due to soiling. In addition, about 25% strings and 10% panels were found be underperforming within each array. The techno-economic analysis revealed that Solar F2D2 has the potential to deliver addition revenue of $10,000/MW/annum through improved solar farm yield.

Apart from the demonstration of the performance of Solar F2D2, the project showed that the hidden underperformance can account for a substantial loss of generation and therefore it is essential to have mechanisms and procedures in place for the advanced monitoring of solar farms. One of the key achievements of the project was the high level of engagement with solar industry. Throughout the project a number of meetings and presentations were held to engage solar industry with the outcomes of this project and to receive feedback. Future technological advancements will rely on such effective collaborations between universities, government and industrial organisations.

II. What is Solar F2D2?

'Solar F2D2' – which stands for 'Solar Farm Fault Detection and Diagnosis' is University of Queensland's newly developed solar farm reliability enhancement tool. It is an all-in-one package that automatically detects and locates any faulty/underperforming panels in large solar farms that are spread over hundreds of hectares of land and comprise of hundreds of thousands of panels. Solar F2D2 is also capable of automatically identifying the cause of panel underperformance. As well as this, it predicts panel soiling levels and provide guidance about 'when and where' solar farm should be cleaned to optimise use of available cleaning resources. Solar F2D2 requires the solar farm voltage and current DC side measurement data available at solar farms.

Hidden panel underperformance costs solar farms from 5%-20% in unanticipated losses. It is expected that Solar F2D2 will mitigate a substantial portion of these losses resulting in millions of dollars of saved revenue for solar farms.

Figure 1 below summarizes the input data requirements, overview of the technology and the applications of Solar F2D2.

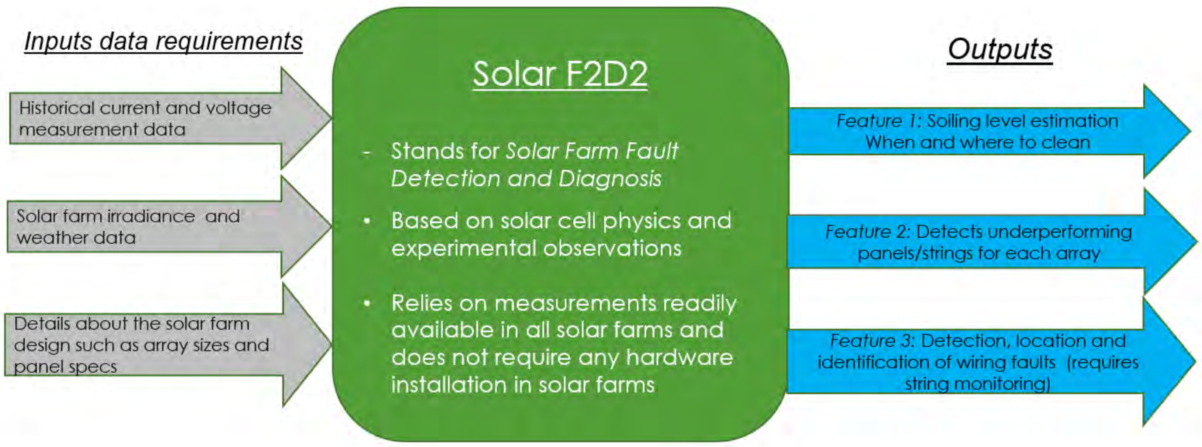

Figure 1: Overview of Solar F2D2

III. Project Aims

The main objectives of this project were to

(I) Establish a data interphase between monitoring boxes at Gatton Solar Farm and UQ's Research Data Manager (RDM).

(II) Demonstrate performance of Solar F2D2 on a section of a solar farm. In particular demonstrate the following features:

a. diagnosis of underperforming panels using array level measurements – estimation of number of strings and panels underperforming for each array
b. Estimation of soiling levels at each array

(III) To evaluate the economic value that can be derived by the use of Solar F2D2.

IV. The pilot project site description

The pilot trial was run at UQ's 3.3 MW Gatton Solar farm located in UQ's Gatton Campus and is 80 km from UQ's main St Lucia campus. Gatton Solar Farm comprises of fixed axis, single-axis tracking and dual-axis tracking technologies. Altogether Gatton Solar farm comprises of 37,000 thin-film panels. The trial of Solar F2D2 was run on the fixed axis part of the solar farm. The whole fixed area is divided into two identical arrays each comprising of 240 strings with each string comprising of 15 panels. Solar F2D2 was implemented on one of the arrays (shown in Figure 2).

Figure 2: Pilot project site to trial Solar F2D2 (Location: UQ Gatton Solar Farm)

V. Summary of the key outcomes/Findings

- ***Team:***
  A team for Solar F2D2 has been established where each member has a well-defined role. At present, there are seven team members in the Solar F2D2 team with roles including technical lead, software lead, hardware lead, business development and commercialisation.

- ***Datalink setup*:**
  Installation of string level monitoring at University of Queensland's (UQ) Gatton Solar Farm was completed to monitor 72 string at a sampling rate of 5 seconds. A datalink was setup to stream data from the monitoring control box located at the Gatton farm to UQ's RDM.

- ***Solar F2D2 validation – array specific soiling level estimation:***
  Testing of Solar F2D2's soiling level prediction feature (named PVClean) using Gatton Solar Farm data for years 2016 and 2019. Soiling of panels results in reduction in the production of solar farms and is the biggest challenge faced by solar farm owners and operators in Australia and abroad. Solar F2D2/PVClean revealed that 5-10% of power production was reduced at Gatton farm due to soiling. This is despite the fact the Gatton gets a good annual rainfall.

- ***Solar F2D2 validation – array specific underperformance estimation:***
  Estimation of the number of strings and panels in each array that are underperforming in the pilot project section of Gatton solar Farm. The latest version of Solar F2D2 is applicable to all solar farms regardless of the type of monitoring system. Approximately 25% strings and 10% panels were found be underperforming within each array.

- ***Solar F2D2 - Value proposition:***
  Value added by Solar F2D2 is estimated at $10,000/MW/year. This estimate is solely based on the estimated increase in power yield through the prompt detection of hidden underperformance of panels/strings using Solar F2D2.

Some further details about each of the outcomes are provided in the following sections.

VI. Solar F2D2 team

A strong collaborative team has been formed run the tasks associated with Solar F2D2. The key members and their roles are summarised as follows:

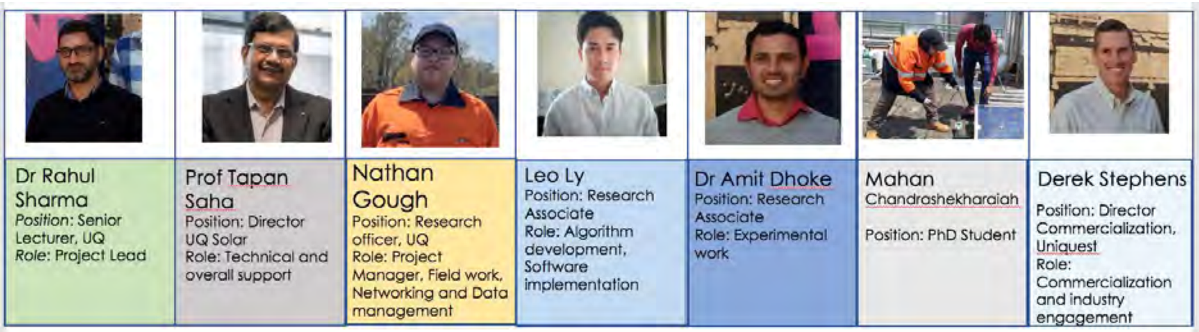

Figure 3: Solar F2D2 key members

VII. Monitoring boxes for Gatton Solar Farm and establishment of a datalink between Gatton farm and UQ-RDM

The design of string monitoring boxes was finalised through a series of discussions with Weidmuller Australia. The boxes were delivered in the last week of July and were installed in Gatton Solar Farm during August-September 2020. The boxes monitor 72 strings at Gatton and have been providing data from October onwards to trial Solar F2D2.

The Gatton monitoring system was designed as a testbed for string-level current monitoring hardware and software. The main aim was to reliably collect high time-resolution DC current readings and then transmit those readings to the University of Queensland's Research Data Manager (RDM) cloud based storage system for later analysis. The broader aim is to evaluate and establish pathways to acquire data from solar farms for processing using Solar F2D2. The measuring devices, their associated equipment, and their enclosures were developed in partnership with Weidmuller and the installation and testing of the enclosures was done by Solar Hybrids Conversion Pty Ltd.

Hardware

The measurement hardware consists of resistive shunt based Transclinic 16I+ 1K5 L devices, powered by a 24V DC supply running from the PV string voltage. The Transclinics are connected to a Modbus network over an RS-485 physical layer. In this deployment, there are two rows containing three Transclinic monitoring devices, and one row that contains two Transclinic devices. Within a row, the Transclinics are connected to each other by RS-485 and to a radio that allows communication to a controller mounted on the UQ Solar Research Hut building. The radio link is transparent to the Transclinic devices and the controller sees one Modbus network with each Transclinic reporting its measurements to the controller. These measurements (in the current configuration) include 8 string currents, the PV system voltage, PCB temperature of the device and several event and status flags.

The system controller is a Weidmuller UC20-WL2000-AC "Automation Controller" running Weidmuller's "u-create web" system software. The controller interfaces with the UQ network by running an OPC UA server with the tags from the Modbus devices that we are interested in defined in the server's namespace. The controller is running an application that regularly polls the Transclinic devices over Modbus and then inserts this data into the OPC UA server, ready to be read over the network. The poll rate is configurable through the controller's web interface, which is also accessible through the UQ network. This allows us to apply software updates or configuration changes to the controller from UQ St. Lucia, over the network.

Software

The second part of the project was the development of data-logging software to enable us to store the stream of data from Gatton at UQ. An application, written in Go, was developed to connect to the OPC UA controller running at Gatton and create a subscription to the string current, system voltage, temperature and status tags that were available. This creates a stream of updates from the controller at Gatton to the software running at UQ. These updates on sensor readings and device status are inserted into an SQLite database locally to create a structured representation suitable for the application of fault-finding or PV shading algorithms. These SQLite databases are then stored on RDM to enable access by researchers and academics, along with details of the database schematic.

The application has configurable properties to enable the person running the experiment to set the list of tags they are interested in, as well as details such as the network location of the controller and any authentication that may be needed to connect to the controller. The OPC UA subscription contains a mechanism to specify how often individual monitored items should be updated and this is exposed to the user as an option to specify on program startup. Currently, as the software is running on a trusted network, where there is minimal authentication with the OPC UA server on the controller, but this can be changed to require anything from username and password authentication to mutual authentication using TLS client and server certificates. These options are exposed in the configuration file and the security policy is defined by a startup option.

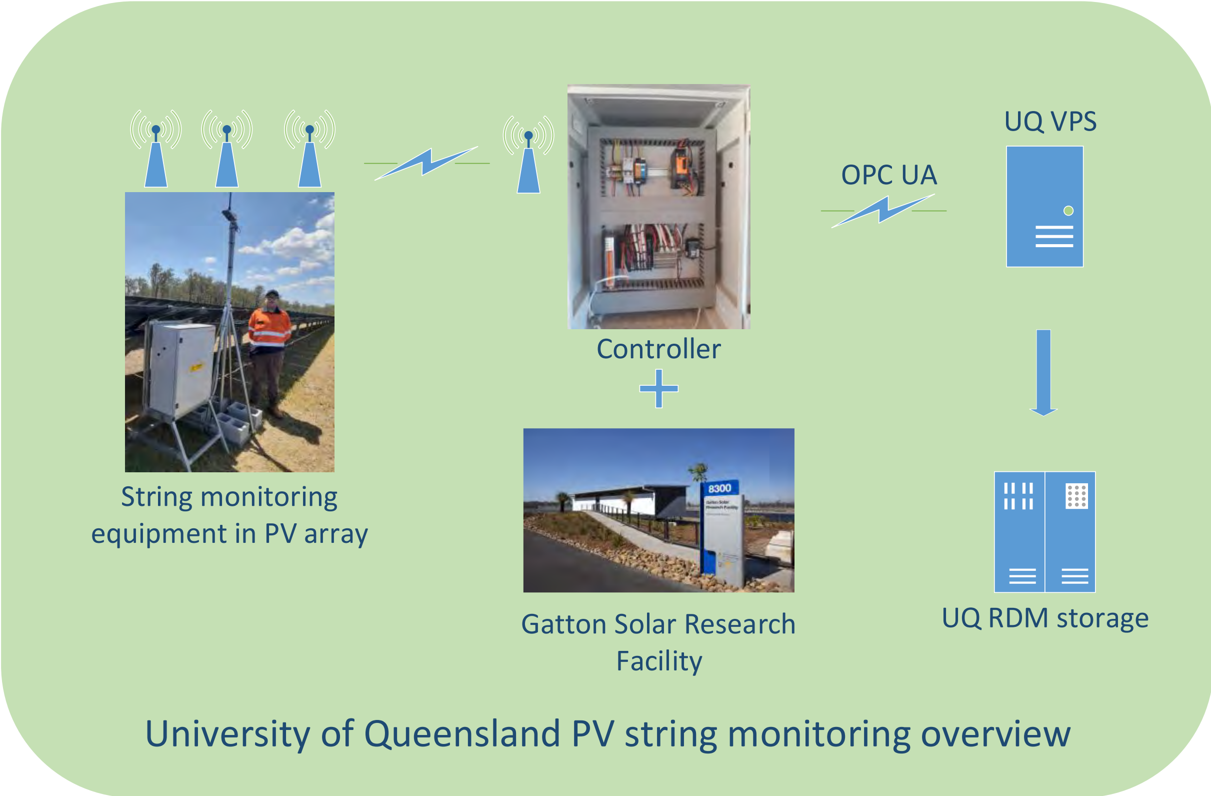

Figure 4: University of Queensland Gatton Solar farm PV string monitoring overview. Setup comprises of Weidmuller monitoring boxes and is part of Solar F2D2 trial installation

VIII. Soiling level prediction using Gatton Solar Farm data

For soiling level prediction, Solar F2D2 comprises of a tool called PVClean. PVClean is capable of performing the following two tasks:

- Predicts the soiling level on the panels on various sections of solar farms
- Advises the solar farms O&M team in terms of 'when and where' the solar farm should be cleaned to make optimum use of their available resources to deliver best possible improvements in power yield

PVClean is based on a mathematical and computational algorithm to predict and quantify the soiling loss level on PV modules, followed by a path finding method that suggests the shortest path that connect all the modules to clean them most effectively. Figure 5 shows a screenshot of the PVClean user interface.

Figure 5: SolarF2D2-PVClean user-interface

The reduction in power production in solar farms can be due to a variety of reasons such as panel soiling, degradation and temperature effects. The key feature of PVClean is that it filters out the effects of panel degradation and temperature and estimates the reduction in power output solely due to soiling.

Sample results

The full details of the algorithm are not included in this report but rather a summary of the application of PVClean on a section of Gatton Solar Farm (Figure 2 shows the exact location) using 2016 and 2019 data are included. Figure 6 to Figure 9 show sample results of validation of Solar F2D2-PVClean using Gatton data. Figure 6 shows the soiling level prediction using existing yield-based soiling level estimation method that do not consider the effects of degradation and temperature. Figure 7 shows the soiling level estimation using Solar F2D2 – PVClean for the same 5 arrays. The soiling levels are plotted against sample numbers that span the whole 2016. Soiling levels range from 0 (no soiling) to 1 (complete loss of power due to soiling). Figures 8 and 9 show that correlation of the monthly soiling levels predicted by Solar F2D2 with the monthly rainfall data from Gatton.

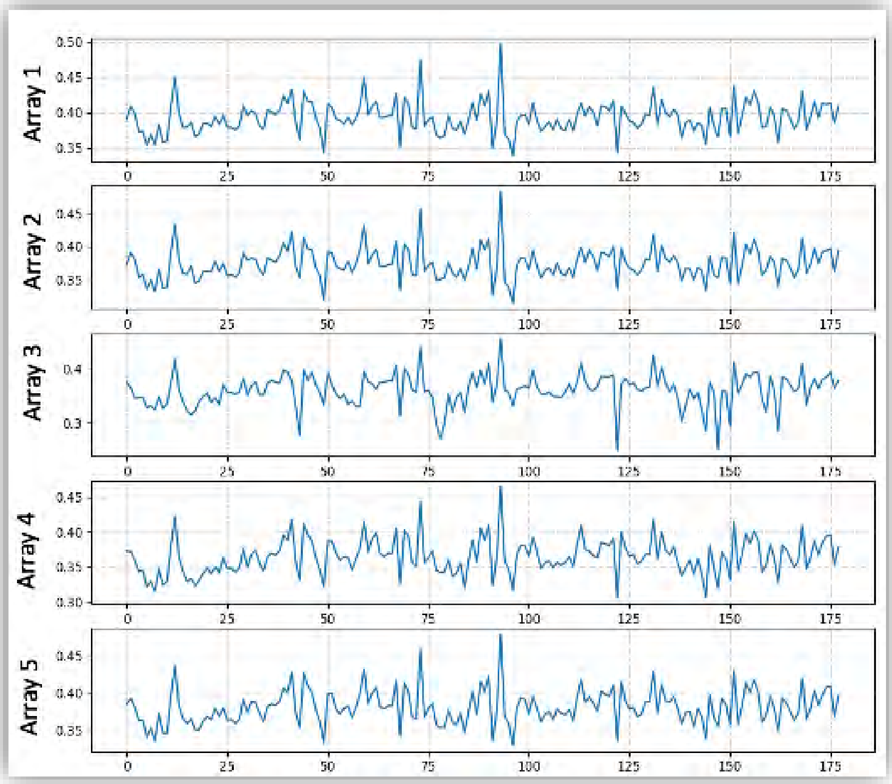

Figure 6: Sample results using 2016 data: Soiling level prediction using existing methods that do not consider the effect of degradation and temperature. X-axis represents the number of samples. Soiling levels range from 0 (no soiling) to 1 (complete loss of power due to soiling)

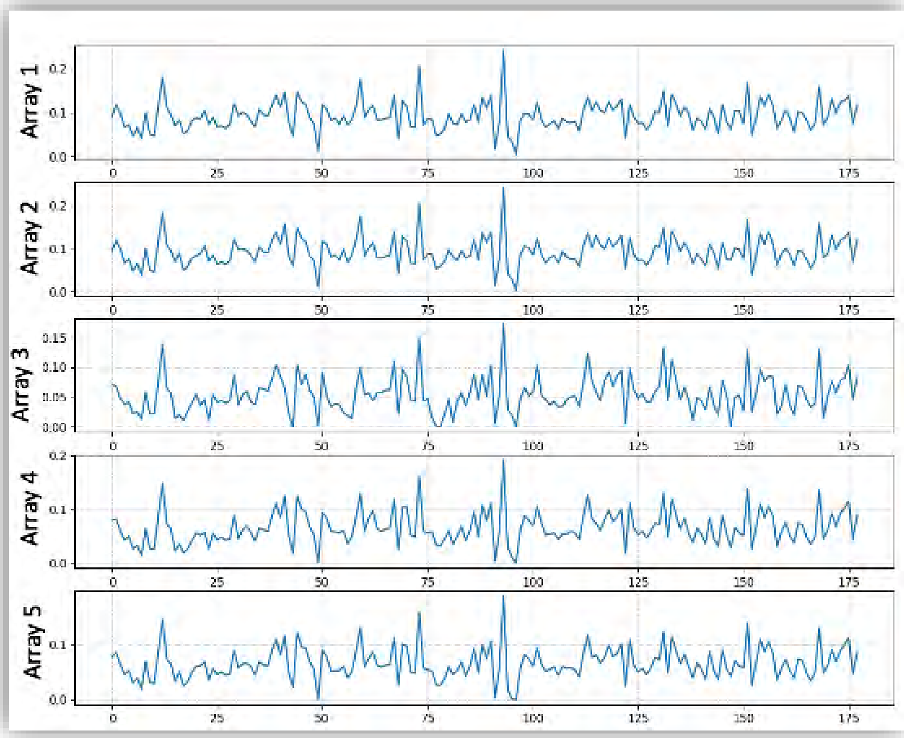

Figure 7: Sample results using 2016 data: Soiling level estimation using Solar F2D2 - PVClean using 2016 data for the same 5 arrays. The results show that PVClean is capable of estimating accurate soiling levels. X-axis represents the number of samples. Soiling levels range from 0 (no soiling) to 1 (complete loss of power due to soiling)

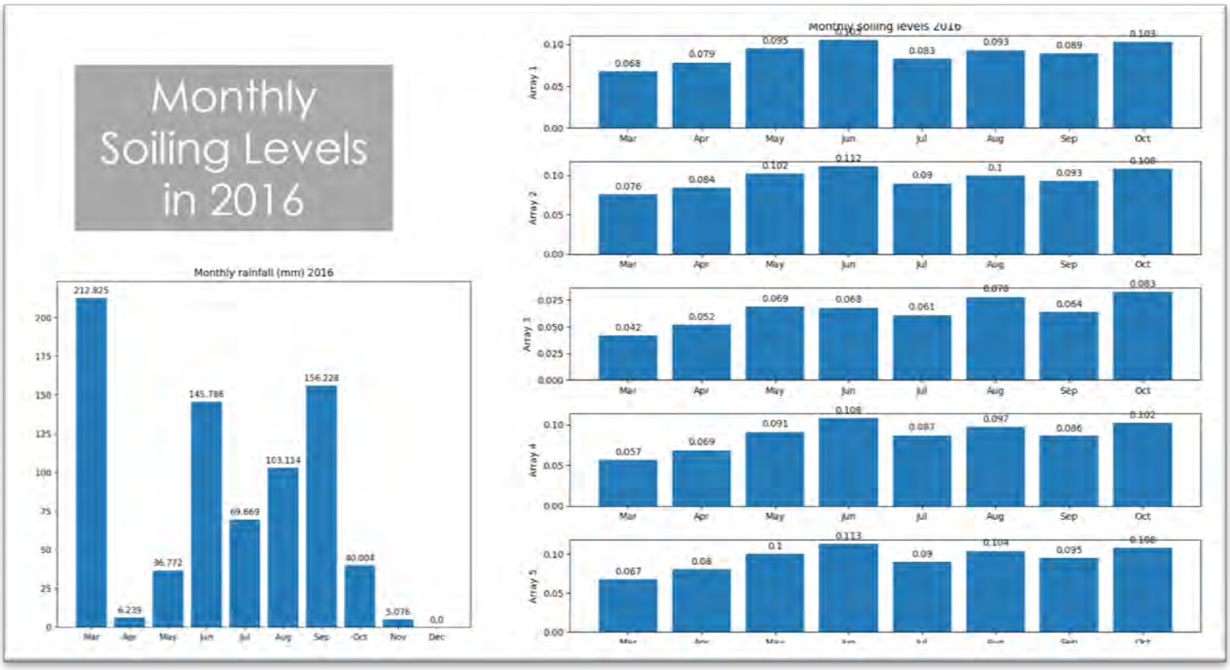

Figure 8: Monthly soiling levels as estimated by Solar F2D2 – PVClean using 2016 data and the monthly rainfall data. Soiling levels range from 0 (no soiling) to 1 (complete loss of power due to soiling).

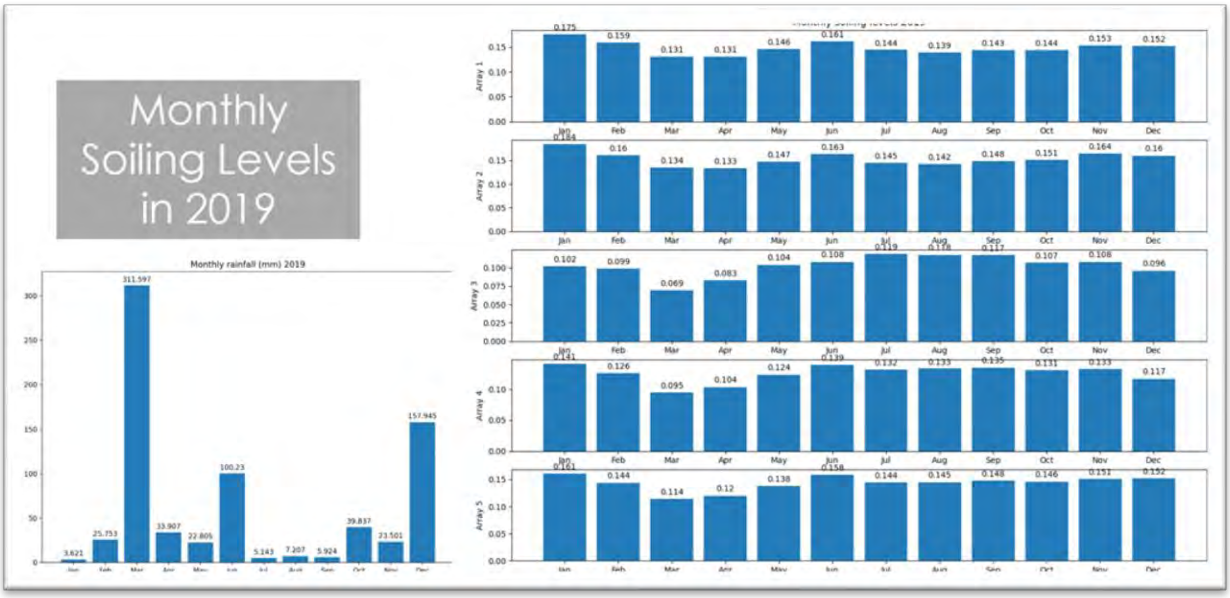

Figure 9: Monthly soiling levels as estimated by Solar F2D2 – PVClean using 2019 data and the monthly rainfall data. Soiling levels range from 0 (no soiling) to 1 (complete loss of power due to soiling).

Some key observations:

- Array level soiling levels were found to range between 5% to 10%. This is despite the fact that Gatton solar farm region gets good amount of rain throughout the year. This indicates that cleaning of panels cannot be solely dependent on rainfall.
- Soiling levels vary from array to array even though the arrays are located adjacent to one another. In large solar farms that are spread over hundreds of hectares of land, the variations in soiling levels from array to array are likely to be significant. Consequently, optimum allocation of solar farm cleaning resources should consider array specific soiling levels to schedule solar farm cleaning in a way to maximize yield improvements.
- In addition, the panels in the trial section of Gatton farm visually look dirt-free. The close inspection reveals a thin layer of dirt deposit which otherwise can go unnoticed. This shows that visual inspection alone is likely to be insufficient to evaluate the soiling related reduction in power output in solar farms.

IX. Prediction of number of underperforming panels and strings using array level measurement

Solar F2D2 is capable of estimating the number of strings and panels underperforming in each array using array level measurements that are readily available in all large scale solar farms in Australia and abroad. The key idea behind this approach is the establishment of a relationship between underperforming panels and strings within an array and the maximum power point (MPP). The full details are not included in this report. However, the main idea is demonstrated in Figure 10. The plot demonstrates the relation between maximum power point and the number of underperforming panels. It is found that there is a systematic trend between MPP value changes with respect to the level of underperformance in an array. Therefore, based on the actual measured power, the range of number of underperforming panels and strings can be estimated.

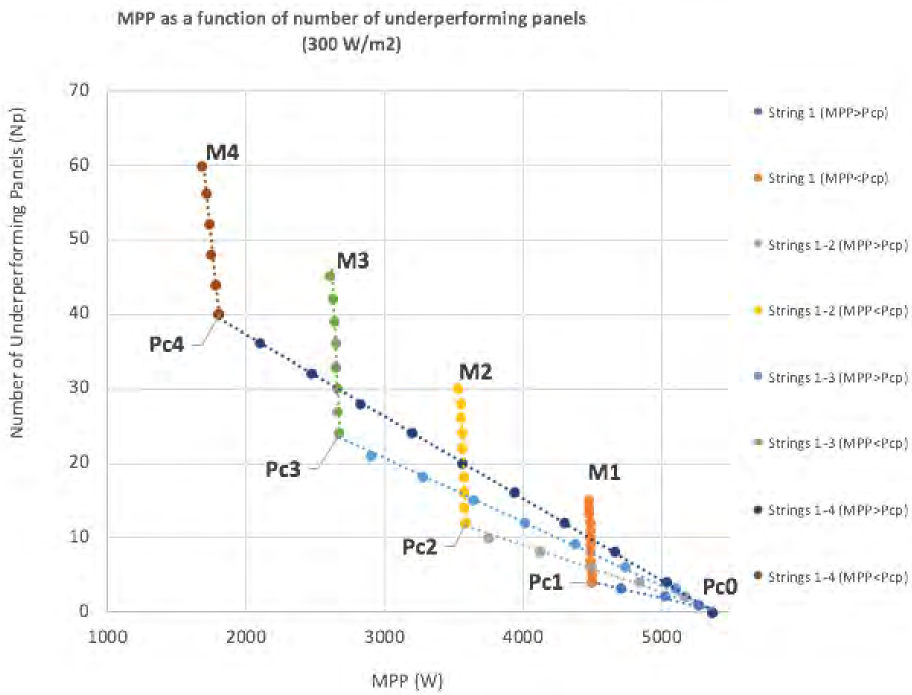

Figure 10: Number of Underperforming panels vs MPP

Table 1: Estimation of the number of underperforming strings and panels within each array using Solar F2D2 with underperformance threshold set at below 50% of the expected ideal power output

With underperformance threshold = $0.5 \times P_{MPP,Ideal}$			
Array number	Number of Underperforming Strings (% of strings underperforming in each array)	Number of Underperforming Panels (% of panels underperforming in each array)	Measured maximum power (kW)
1	23 (24%)	137 (9.5%)	11.5
2	27 (28%)	143 (10%)	11.3
3	24 (25%)	127 (8.6%)	11.5
4	26 (27%)	142 (9.8%)	11.3
5	25 (26%)	153 (10.6%)	11.4

Sample results:

This feature of Solar F2D2 was evaluated on the trial site of of Gatton Solar Farm. The array level data from 5 arrays was used. Each array contains 96 strings. Each string contains 15 panels. The 2019 data was divided into 6 chronological sections (each section spans over 2 months). Maximum power of each section was then calculated using the array voltage and the current of each array. Both voltages and currents were pre-processed to eliminate the effect of temperature. The maximum powers of every array as observed over 5 arrays follow a uniform degrading pattern i.e. drop in performance. The validation is performed using two underperformance threshold levels: At 0.5 x $P_{MPP,Ideal}$ (below 50% of the expected ideal output) and at 0.7 x $P_{MPP,Ideal}$ (below 70% of the expected ideal output). The sample results are summarised in Table 1 and Table 2.

Table 2: Estimation of the number of underperforming strings and panels within each array using Solar F2D2 with underperformance threshold set at below 70% of the expected ideal power output

With underperformance threshold = $0.7 \times P_{MPP,Ideal}$			
Array number	Number of Underperforming Strings (% of strings underperforming in each array)	Number of Underperforming Panels (% of panels underperforming in each array)	Measure maximum power (kW)
1	46 (48%)	112 (7.8%)	11.4
2	54 (56%)	121 (8.4%)	11.3
3	47 (49%)	119 (8.3%)	11.5
4	51 (53%)	118 (8.3%)	11.4
5	49 (51%)	116 (8.2%)	11.4

Some key observations:

- Approximately 25% strings and 10% were found to be producing below 50% of the expected output within each array. If the This is substantially higher than the expected <2% annual reduction in power output as per the panel specifications. The proportion of underperforming strings and panels is even higher if the underperformance level is set at 70% of the expected power output.

- The underperformance is unlikely to be detected by either protection devices or even through visual inspection because visually the panels look in good condition. Therefore, it appears necessary to have procedures in place to estimate array level degradation and underperformance to maximise the power output from solar farms.

X. Techno-Economic Analysis:

At present we have information from Gatton solar farm production, O&M frequency, export price and estimates about underperformance using array level measurements. Based on available information we have estimated that Solar F2D2 is expected to deliver more than $10,000/MW/annum in improved revenue. Some further details are as follows:

Value derived from effective soiling detection and guidance about when and where to clean:

Net increase in revenue,

$$R_{Soiling}(\$/annum) = \frac{(y-x)}{100} \times E \times p$$

where, *y* represents percent improvement in power yield by Solar F2D2 guided cleaning, x represents percent improvement in power yield without solar F2D2 guided cleaning, *E* is the expected annual energy production in MWh and *p* is the price in $/MWh.

For Gatton, based on out pilot project these values are *y* – x > 2%, *E* = 6,000 MWh, *p* = 15 c/KWh.

Consequently, for Gatton Farm $R_{Soiling} = \$18{,}000$ per annum.

Value derived from underperformance detection:

Typical frequency of O&M for Gatton 6-12 months. This is representative of the standard practice for O&M in solar farms.

Assumption: x% of panels are underperforming for average 3 months where underperformance is defined as below 70% of the expected output. Therefore, potential revenue improvement from Solar F2D2 through prompt diagnosis of underperformance:

$$R_{under} = \frac{x}{100} \times \frac{(1-0.7)}{2} \times E \times p$$

Assuming x = 10%, $R_{under} = \$13{,}500$ per annum.

Revenue improvements through improved production for Gatton = $R_{soiling} + R_{under} = \$31{,}500$ per annum. Gatton solar farm capacity is approximately 3 MW.

In summary,

- Value driven from Solar F2D2 is estimated at $10,000/MW per annum subject to the conditions assumed in the calculations.
- Solar F2D2 derived benefit value for solar farms as $10,000/MW per annum translates to $1M per annum of improved revenue for a 100 MW solar farm.

XI. Industry engagement

List of industries to which Solar F2D2 features and results were presented:

- Siemens
- Weidmuller
- Genex Power
- Blueshore Energy
- UGL
- Rittal
- Rio Tinto
- WSP
- NOJA Power
- ENcome
- Edify Energy (Gretal Solar Farm) team
- Nuvotron

XII. IP update:

International application published under the Patent Cooperation Treaty (PCT)- International Publication Number WO2020/087128A1 was filed on 31-10-19. International Publication Date was 7-5-20. Approved by UniQuest for the filing of national phase entry in Australia, Europe and the United States (PAT-02329-AU-02; PAT-02329-US-01; PAT-02329-EP-01)

XIII. Next steps

1. *Setting up of Solar F2D2 as a start-up:* Solar F2D2 team is in discussion with potential investors to secure funding to set up a start-up for Solar F2D2. Initially, Solar F2D2 will be offered as a service.
2. *Detailed market analysis and business model development:* In the next 2-3 months a detailed market analysis will be performed to establish best business model for establishing Solar F2D2 as a spin-off.

3. *Commercial trial:* Having completed the pilot trial, the next step is to run a commercial trial to test Solar F2D2 on a large solar farm. Solar F2D2 team is already in discussions with solar farm entities to collaborate to run a commercial trial.