From inspection to asset management with UAV integration in utility-scale solar PV Systems – Designing PV Insight

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Abstract

This document is the extended abstract of a master thesis dissertation carried out through a thesis-related internship at the Portuguese start-up Pro-Drone. The document analyzes the design and first stages of development of an innovative solution for utility-scale solar PV plants inspections with UAVs, based on in-house inspections and temperature data processing that enforces the O&M of the plants. The work is structured in three different blocks that have been developed simultaneously during the project, but that have been separated in the final report for a better understanding of the results. The three blocks are the solution design, the technical development and the financial analysis, introduced and concluded at the beginning and the end of the work, respectively.

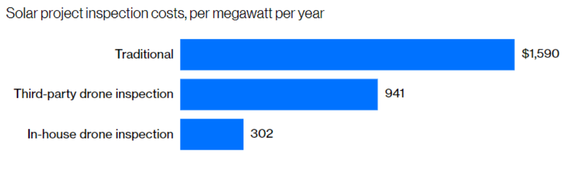
Keywords: solar PV, utility-scale, UAV, in-house, temperature.

I. Introduction

Climate change is evolving fast and its effects are pushing to implement with urgency policies favorable to clean energy generation. The increasing electric demand worldwide enlarges the challenge of decarbonizing the energy sector. Sustainable energy (including nuclear) is meant to be 50% of the global electricity mix in 2040 [1], which might not be enough.

Innovation in renewable energy is playing a very important role in the energy transition. Technology is evolving fast and dropping down prices thanks to an exponential growth in technological innovations. Digitalization of the economy is including the energy sector and digital solutions related with energy generation, consumption and management are supporting the growth.

Unmanned Aerial Vehicles (UAVs) can play an important role in this digitalization since the data collected by a drone is homogeneous and is easier to process in digital tools. Drones are cutting down operational costs in renewable energy thanks to the easiness of data collection in comparison with traditional methods. For example: in wind power, blade inspections are now carried by drones instead of by humans hanging with ropes from the nacelle, increasing the reliability of the data, the time efficiency of the inspection and the safety of the operator. In solar PV, they cut down significantly the time spent in surveys on the solar field, and they are forecasted to cut down costs of inspections by a factor of five in case of being done in-house, as can be seen in the following figure.



Source: Bloomberg NEF
Note: Assumes a 10-megawatt solar project without tracking system, in Germany

Figure 1. Solar project inspection costs [2].

The core of the document is a business case suggested by the company Pro-Drone, the company where the author has carried the thesis-related internship. The company has a mature solution for inspecting wind turbine blades and wanted to analyze the possibility of expanding to the market of solar PV with an innovative solution that can distinguish among the already existing ones and increase the value of the company. The document explains the initial steps of the solution until the first validation of the minimum viable product.

II. Solution Design

In this part of the document, the business approach to perform the design of the solution is explained. After an initial market analysis, the PV market is identified as very attractive to develop UAV technology due to the growth that is experiencing and that is forecasted to continue in the following years. The following figure depicts the growth.

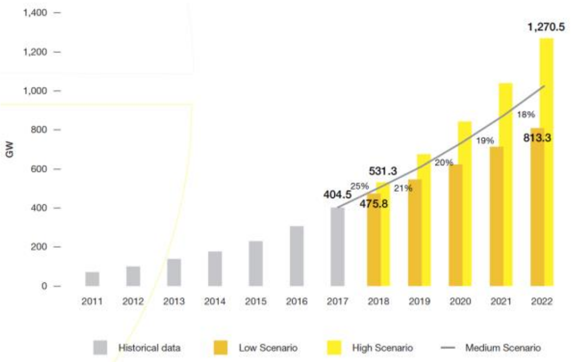


Figure 2. Global solar PV market forecast [3].

Drone solutions are being implemented in the market for some years already. The business model followed by most of the companies offering UAV technology is to offer a survey on the PV plant as a service and present the results in a report. The main competitors have been analyzed and the results state that offering their solution as a service makes their price rise high to pay off logistic costs of data collection, and none of them is going deep into the data processing. In order to enter the market differentiating from the existing solutions and adding the most value to the customers, a new player would need to allow the customer to do inspections in-house as well as process the data in full detail and full focus on solar PV technology. This way, the costs for the customer would be minimized through a do-it-yourself data collection and the value out of the data processing would be maximized.

A scientific research has been carried out to understand how to optimize the data collection and the data processing inside the inspections by analyzing the most common failures in solar PV panels and the ways to identify them with a UAV. The results suggest that every failure in a PV module generates a heat loss which increases the temperature of the cell. Hence, failures can be spotted through IR imaging and the cause of the failure can be detected by patterns in the same IR image or through RGB imaging [4].

A common failure that is not taken into account in the existing solutions is micro cracks. Micro cracks are inside all PV panels without affecting power production significantly but in some cases they grow big and can cause a big power loss [5]. They are easy to detect with an image technique called electroluminescence (EL) but that requires totally dark conditions, which is unfeasible to acknowledge with UAV technology. RGB can also detect micro cracks but requires high resolution in the image, which would mean that the drone needs to fly very close to the panel. The closer the drone is to the panel, the longer it takes to carry the survey.

Design Thinking through Validated Learning

Results of the research generate the first set of assumptions that constitute the initial design of the solution. This design is based on an easy-to-use cloud platform that can support automated in-house inspections with a click of the mouse and can offer fully processed information regarding issues in the panels such as micro cracks, bird droppings or browning, supported by IR and RGB imaging. The following figure shows the main value proposition of this initial solution.

Figure 3. Value proposition of the initial solution.

The customer activates a data collection and accesses the processed data through the cloud platform, which disposes the whole plant digitally and offers RGB and IR pictures of the defaults detected automatically in the data processing. The drone is fully available at the plant, set and ready for carrying an inspection at any moment. Hence, every PV plant has its own drone for data collection and access to the cloud platform for the data processing. The drone runs on automated flights so the personnel in the plant can operate it.

This initial design does not take into account the logistics of the data collection neither the will of the potential customer; it is simply an initial ideal design that will need to be validated to shape it into a more realistic solution.

In order to validate the initial design, the method of validated learning is followed. That method makes emphasis in building up a build-measure-test loop in the initial development phase of the solution, so the different features of it can be tested with real customers to then measure the reactions and improve the product. The overall goal of the process is to minimize the time spent in useless development and maximize the value that the product brings to the customer.

Following the method, direct contact with the potential customers is stablished. Using the customer portfolio for wind blade inspections, and adding more contacts acquired through a cold calling round, two consecutive rounds of interviews are set with potential customers and experts in the sector of solar PV. The interviews are done via phone and video calls in most of the times, but also through personal meetings at the customer's offices. A time gap in between the two rounds is set to apply the feedback from the first round, shape the solution and validate the new design in the second round. At the end of the validation process, the solution is shaped according to the market preferences, and the value proposition and business model are clear. Then, the solution is ready to start development.

Solution's Design

The final design of the solution is a cloud platform that generates automated flight plans and processes the data to show it to the customer synthesized. The main goal of the tool is to increase the reliability of the data collected over the solar field as well as focusing the data processing specifically in solar PV. The customer segment has two different components: the O&M team of the solar PV plant and licensees that use the inspection to provide survey services. For both cases, the data collection is simplified by ensuring reliable automated flights with flight parameters optimized for solar PV data collection, so unexperienced drone pilots can carry the flights. The flights collect IR and RGB images, and the drone is seen as a tool to be owned by the customer and use in different PV plants. For an optimum IR and RGB data collection, dual sensors are recommended so both can be done in the same flight. The following figure shows a model from FLIR.

Figure 4. FLIR dual sensor [6].

Regarding the processing and display of the data, the images collected are stitched together in IR and RGB maps, and the IR imaging is processed through a classification model that identifies each panel in the image and reads temperature records inside it, providing for every panel statistic values such as maximum, minimum and average temperatures. This data is later processed to identify defected panels and assess the customer with the predicted power lost that the defects are creating in the plant.

The value proposition of the solution involves the drone as a tool with software support to operate it, the track record of inspections inside the cloud platform that allow the customer to compare past inspections and the full focus on the data in both the collection and the processing, ensuring optimum parameters for data collection in solar PV and reliable processed data that has a positive insight in the decision making of the company. The solution is named PV Insight.

III. Technical Development

The technical development of the work has two main blocks: the data collection and the data processing. Those blocks set the criterion to optimize the processes of data collection and processing basing on different mathematic and physic principles. At the end of the second, an extra block with a real data collection and processing is explained, in which the criterions stablished in the first and second blocks are validated in tests in a PV plant in Portugal.

Data Collection

The data collection focuses on the parameters required to define a proper automated flight. Basing on the optics principles behind a sensor and the size of the minimum failure that needs to be identified on the ground, it sets the processes and calculations to follow to obtain the optimized flight parameters for a survey on solar PV panels. The calculations are done for an IR sensor, but the methodology for an RGB flight would be the same. Taking into account that the flight is done with a dual sensor, it is considered that the limiting factor in the flight is the quality of the IR images, since the RGB sensor presents usually a much better resolution than the IR.

The parameters obtained are tested in Mission Planner, an open-source flight planning software. The plant used for the survey is in the south of Portugal, and a sensor with the same characteristics is selected for the flight. The output of the simulation validates that the calculations done are correct, and provides other flight parameters such as the flight time, which is of 13 minutes per MW. Results state that in-house inspections are feasible. The following figure shows the overview of the flight plan over the PV plant in Mission Planner.

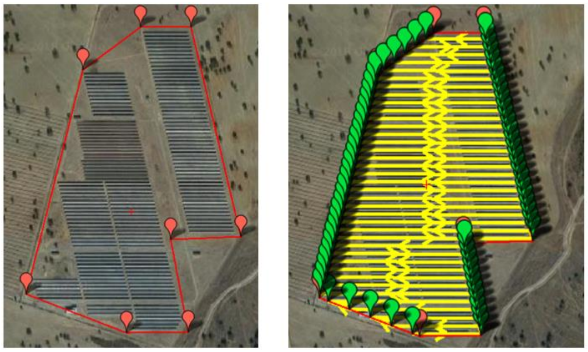


Figure 5. Automated flight over a PV plant [7].

Data Processing

The data processing focuses on the analysis of the temperature data inside the panels. Leaving image processing aside –out of the scope of this document and developed by other members of the team-, the processing focuses on the analysis of temperature data inside the panels, provided by the image classification model. A complementary model is built on Python using the data science library *Pandas* to analyze the temperature data in CSV files and asses on fault detection, power losses and warranty claims on the panels. The data set has rows as panels and columns as features, such as temperature maximum.

Fault Detection

In the fault detection part, the model classifies the panels into defected and not defected according to the temperature differences between the maximum and the average temperature inside each panel. It is assumed that if a panel has a hot spot, part of the panel will present a temperature gradient with the rest of it. Checking the temperature data, it is assumed that this gradient can be applied between the maximum temperature of the panel and the average. Also, it is identified that a panel is defected if the average temperature is over a given value, independently of the maximum. The two criterions are summarized in the following expressions.

$$T_{max} - T_{avg} > 1°C \qquad (1)$$

$$T_{max} > 35°C \qquad (2)$$

The values of the minimum gradient and lowest maximum temperature to set a panel as defected are based on a visual inspection carried out on real maps. The model applies the criterion to each one of the panels in the data set and classifies them by adding a binary variable, set as 1 in case of defected panel and 0 in case not.

Power Loss Assessment

For the power loss assessment, the data to check in the CSV is the minimum and the average temperatures. The analysis is based in the thermal coefficient of power, which states that for temperatures over the STC, a solar PV cell loses efficiency as the temperature increases [8][9][10]. The main expressions used to calculate the power losses in the panels are the following.

$$\begin{aligned} P_{u,max} &= P_c * \eta_{max} = \\ &= P_c * [\eta_{STC} + (T_{min} - T_{STC}) * TC] \end{aligned} \qquad (3)$$

$$\begin{aligned} P_{u,real} &= P_c * \eta_{real} = \\ &= P_c * \left[\eta_{max} + \left(T_{avg} - T_{min}\right) * TC\right] \end{aligned} \qquad (4)$$

$$P_{los} = P_{u,max} - P_{u,real} \qquad (5)$$

By applying those expressions, the power losses per panel are calculated and added as integers in the data set, adding one integer per panel. The cumulated losses and cumulated useful power are also computed while the model iterates through all the rows of the data set.

Warranty Assessment

The warranty assessment analyzes the power losses in the panels that have been set as defected by the default classification and compares them with the minimum warranty conditions of the panel regarding power production. Those conditions can be accessed online in the webpage of the manufacturers. The model sets as positive the binary variable –hence, declares as claimable for warranty- those panels that fulfill the following two conditions.

$$[\mathit{Classification} = \mathit{1}] \text{ AND } [P_w > P_{u,real}] \qquad (6)$$

Final Calculations

At the end of the model, the cumulative values are used to express the cumulated losses in the data set as yearly monetary losses, given the price at which that electricity would have been sold and time constraint being the capacity factor applied to the total yearly hours.

The losses of the given data set are also extrapolated to the whole power capacity in the PV plant in where the data is collected, in order to estimate the economic impact of the losses in a given data set for a PV plant of X capacity, and compare that impact with the O&M budget of the plant, which by literature review has been found to be of around 20 € per kW installed [11].

Real Data Collection and Processing

Real tests were carried out in a PV plant in Portugal at the end of July, 2018. The tests consisted of a flight validations assumption and a small data collection with automated flights, and were carried with rented equipment that consisted of a drone, an IR sensor and an RGB sensor. After the data collection, the first steps of the data processing obtained the IR maps and temperature values for each panel, with all the values needed to run the model for temperature data analysis developed. The model was then put to test to validate its criterion. The following figure shows the IR map zoomed in a defected panel.

Attribute table - zonalstatF :: Features total: 576, filtered: 576, selected: 1

	Class	area	perimeter	_min	_max	_sum	_count	_mean
494	1	1.04883	4.72440	24.053082	25.579748	7912.043945	316.000000	25.038114
495	1	1.06641	4.90728	25.202835	28.589191	8083.566895	308.000000	26.245347
496	1	1.05615	4.60248	25.526552	26.898315	8308.310547	316.000000	26.292122
497	1	1.04541	4.81584	25.956341	37.220028	8720.668945	318.000000	27.423487

Figure 6. IR map with a hot spot and temperature data.

The goal of the tests in data collection was to validate the assumptions that had been taken for the parameters of the automated flight. The results were positive and the data could be collected successfully.

The test for data processing showed that the model for temperature data analysis was processing the criterion correctly, but the results added some challenges to both data collection and data processing. The numerical results of the model are depicted in the following figure.

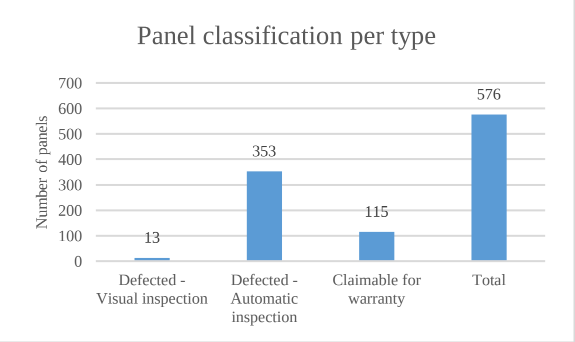


Figure 7. Panel classification per type.

Parallel to the data processing, a visual inspection on the IR maps obtained from the data collection was carried out, identifying 13 defects in the panels. The automated analysis identified those 13 defects, but classified a total of 353 defected panels. The criterion for the classification had been set to follow the minimum gradient identified in those 13 defects in order to avoid false negatives, which caused the appearance of a lot of false positives. In other words, it was preferred to have panels selected as defected by the model but that were selected wrongly and were actually alright, rather than panels selected as alright by the model but that were actually defected. In any case, the high number of false positives required a check on the map to identify the failure in the model.

The issue was identified to come from the low resolution of the IR sensor rented. The IR pictures taken had low resolution and the sensor had some issues with the calibration as well, which created distortions in the IR map. The panels that were selected as false positives were catching pixels from the ground due to this anomaly. Taking into account that the ground was at a higher temperature than the panels in the IR pictures, the phenomenon was increasing the maximum temperature value and affecting the fault detection of the model, based on the temperature data.

The issue affected as well the power loss calculation and the warranty claim, being 115 panels the total set as claimable for warranty. The following figure depicts the classification of the panels by plotting their maximum and average temperatures and showing the dots in different colors according to the different classification. The blue line depicts average equals to maximum temperature, and the red line represents the difference of 1 °C, first criterion for fault detection in the model. The black dotted line is set at 35 °C, representing the second criterion.

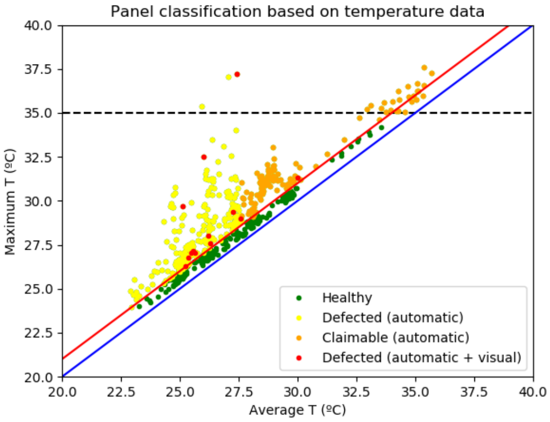


Figure 8. Panel classification based on temperature data.

The results for the power loss calculations and extrapolation to the whole PV plant suggest that the losses are significant in comparison with the O&M budget of the plant. The predicted losses are of 15,421 € per year, whereas the O&M budget is predicted to be of 124.000 € per year; in relative terms, the thermal losses are a 12.44% of the O&M budget. The O&M budget is set at 20 € per kW and year, based on literature review [11].

Conclusions on the results from the real tests are that the data collection is easy and fast, which states that in-house inspections by the O&M team are feasible. However, the issues with the sensor caused problems in the data collection, but it is assumed that with a better sensor the results would improve.

Regarding data processing, it is stated that the model runs the criterion perfectly but the results are distorted by the low resolution of the IR sensor. It would be interesting to compare the losses calculated with the real losses, but I-V measurements on the panels would be required. It is important to remember as well the role of the model, which is not giving a final diagnostic on the status of the panel but carrying an assessment to reduce the time spent in data analysis.

The results of the tests were shared with the customer through an offline MVP that validated the quality of the maps and the approach of analyzing the temperature data. The feedback from the validation was positive, which opens new development scenarios to enhance the solution.

IV. Financial Analysis

The financial model built analyzes the cash flows in the project in a 4 years horizon starting in October, 2018, taking into account the costs of development and the revenues associated. The model separates the balances in trimesters or Qs.

The target market is 10% of the European utility-scale solar PV capacity now, which is meant to be reached at the end of the fourth year. In total, it means 4 GW that, at the price fixed for the solution, could generate yearly revenues of 400.000 €.

The model takes into account four stages, through which the team evolves and the revenue strategy changes. At the first stage, the team is carrying full inspections (data collection and processing) that turn into licensing revenues (only data processing). The strategy is meant to attract more customers at the beginning by offering inspections as a lower price than the market price, and turning into the licensing business model as the solution matures.

The costs taken into account are: equipment, team, trips for commercial purposes, costs of data collection for the first stages, software licenses required and cloud storage costs. The cost of the equipment to test and collect data is considered of 20.000 €.

The revenues taken into account are: inspection revenues, data upload revenues and signup revenues. The prices set are 200 € per MW for full inspections, 50 € per MW for data uploads and 85 € per MW for signup fees.

The costs and revenues are balanced for each trimester. The results of the model are shown in the following figure.

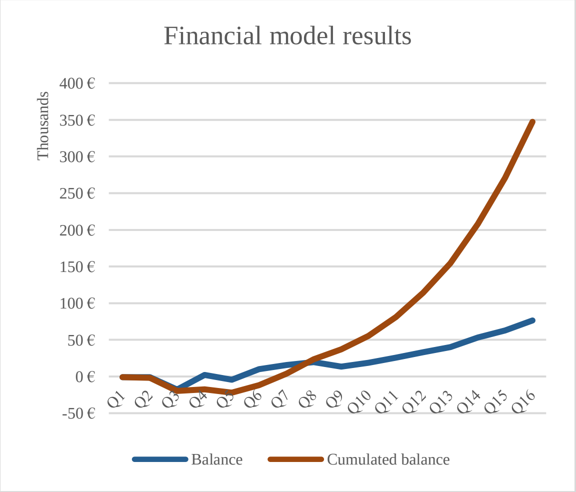


Figure 9. Financial model results.

The results of the financial model suggest the following:

- The breakeven point is reached at Q5, which is relatively soon.
- The investment required is of 25.000 €, given the minimum of the cumulated balance.
- The cumulated benefit at the end of Q16 (end of the fourth year) is of 350.000 €, which is 14 times the initial investment required.

V. Conclusions

In this work, the design of an innovative solution to integrate UAVs in the O&M of solar PV plants has been described. Overall, the solution is technically possible, economically feasible and adds significant value to the final customer. Moreover, it has been set as profitable for the company to develop.

Regarding the design of the solution, the importance of the validated learning in the process must be highlighted. Not only helped to design a new solution that adds more value for the customer but also focused the time spent in development in features that are appreciated. The final design improves the O&M of the PV plant and generates a sustainable business for the company. Moreover, the situation of growth in the solar PV market depict a promising scenario to invest in.

Analyzing the technical development done so far, it can be stated that it fulfilled the initial requirements of the solution: it's possible to process IR and RGB images into maps, extract the temperature data and process it to offer useful information. The model for temperature data analysis has been proven to work correctly and the output adds value by cutting down the time spent in data analysis significantly. However, that should not be the ideal solution to apply. Machine learning could add more value in the automatization of the data processing, but will not be accurate until the amount of data available is significant. For an initial stage, the model built in this work is a good starting point in temperature data processing.

Checking the financial model, it is stated that the solution is very interesting to develop from the point of view of the technology developer, and also from the point of view of the final customer, since it provides cheaper and more reliable inspections on the panels.

For future works stay comparing the power loss assessments with real power data measured on-site, collecting and processing more data preferably with a dual sensor, improving the model to analyze as well the electronics of the PV systems and develop machine learning algorithms to do the data processing in the future.

Bibliography

[1] "Global electricity mix | World Coal Association." [Online]. Available: https://www.worldcoal.org/global-electricity-mix. [Accessed: 07-Sep-2018].

[2] "Drones Poised to Save Big Bucks for Power Companies - Bloomberg." [Online]. Available: https://www.bloomberg.com/view/articles/2018-09-07/drones-poised-to-save-big-bucks-for-power-companies. [Accessed: 11-Sep-2018].

[3] SolarPowerEurope, "Global Market Outlook for Solar Power 2018-2022," 2018.

[4] International Energy Agency | Photovoltaic Power Systems Programme, *Review of Failures of Photovoltaic Modules*. 2014.

[5] M. Dhimish, V. Holmes, B. Mehrdadi, and M. Dales, "The impact of cracks on photovoltaic power performance," *J. Sci. Adv. Mater. Devices*, vol. 2, no. 2, pp. 199–209, 2017.

[6] "Drone Cameras | FLIR Systems." [Online]. Available: https://www.flir.eu/browse/home--outdoor/drone-cameras/. [Accessed: 16-Sep-2018].

[7] "Mission Planner Home — Mission Planner documentation." [Online]. Available: http://ardupilot.org/planner/. [Accessed: 26-Sep-2018].

[8] G.-A. Migan, "Study of the operating temperature of a PV module," *Proj. Rep. Heat Mass Transf.*, 2013.

[9] A. R. Amelia, Y. M. Irwan, W. Z. Leow, M. Irwanto, I. Safwati, and M. Zhafarina, "Investigation of the Effect Temperature on Photovoltaic (PV) Panel Output Performance," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 6, no. 5 November, 2016.

[10] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review," *Energy Procedia*, vol. 33, pp. 311–321, 2013.

[11] NREL - National Renewable Energy Laboratory, "Best Practices in PV System Operations and Maintenance," no. March, 2015.