



A GUIDE TO INSPECTING SOLAR FIELDS WITH THERMAL IMAGING DRONES



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INTRODUCTION

Scale Photovoltaic (PV) Field Efficiency and Output with Drone Thermal Imaging Inspections

Thanks to continued improvements in thermal imaging hardware, software, and drone technology, it is now possible to improve the efficiency and accuracy of solar, or photovoltaic (PV), inspections more than ever. The current practice of manual electric testing is not sustainable at scale and results in slower PV system build outs, increased inefficiencies in identifying potential equipment and construction problems, and delayed repairs to faulty panels and balance of system (BOS) components.

Meanwhile, solar energy use continues to grow dramatically. According to the Solar Energy Industries Association (SEIA), solar use in the U.S. has experienced an average annual growth rate of 50 percent in the last decade, fueled in part by the Solar Investment Tax Credit (ITC) and an estimated 70 percent drop in solar install costs. SEIA anticipates that total installed U.S. PV capacity will more than double over the next five years. By 2023, more than 14 gigawatts (GW) of PV capacity will be installed annually. With installations expected to total 240 GW by 2030, Credit Suisse is also seeing strong markets in the Middle East, Europe, and Latin America as well as the U.S. as solar power becomes increasingly cost effective in relation to traditional, fossil-fuel power creation.

For asset owners, PV inspectors, and drone service providers (DSPs) to meet the growing demand of PV inspection and maintenance, they must develop a deep understanding of thermography, flight operations, and other factors to take full advantage of the benefits of drone-based solar inspection. This will also enable those energy stakeholders and asset owners, specifically, to further maximize efficiencies and outputs from their respective PV systems.

This paper introduces the following topics:

- THE PRESENT STATE OF PV SYSTEM INSPECTIONS
- THE BENEFITS OF LEVERAGING DRONES WITH DUAL THERMAL AND VISIBLE CAMERA SYSTEMS
- HOW TO USE DRONE THERMAL IMAGING FOR PV INSPECTIONS
- WHAT TO LOOK FOR IN A POTENTIAL DSP
- THE LIMITATIONS OF USING THERMAL IMAGING DRONES FOR PV INSPECTIONS

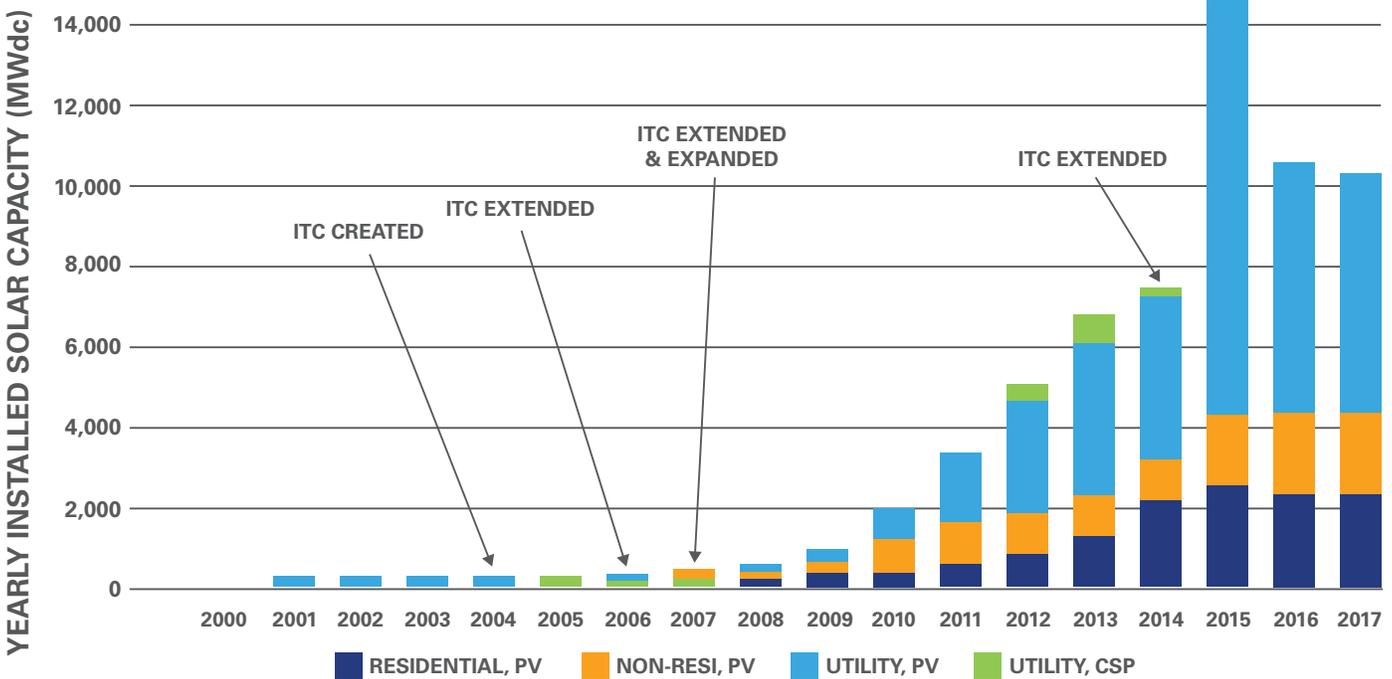


FIGURE 1: Annual U.S. solar installations (Source: Wood Mackenzie Power and Renewables/Solar Energy Industries Association)

COMPARING MANUAL ELECTRIC TESTING TO DRONE THERMAL IMAGING FOR PV INSPECTIONS

Manual electrical testing is the de facto method of inspecting PV systems. Known as IV Curve Tracing, the test is the current industry standard for inspecting and evaluating performance of a solar array. It is applied by trained, highly skilled technicians using handheld testing kits during only ideal environmental conditions such as dry, relatively-clear weather with little to no wind. For the test to be valid, panels must reach a certain irradiance level, and then the panel must meet a minimum and defined watt per square meter.

Each string, or row of panels, scheduled to be tested must be unplugged from the array and plugged into the manual electrical testing device. In addition to the issue of scale, technicians must manually interpret test results to determine the health of the field. This takes hours or days for a small site and significantly more time for a large 100-acre array.

THE PROBLEM CHECKLIST

PV testing technicians manually inspect for five different symptoms of impairments:

- SERIES LOSSES:** Series losses are caused by excessive resistance in the circuit. This can be due to degradation in a particular component, or the wiring between them. The increased resistance can result in further degradation and permanent damage. Bypass diodes help to mitigate this.
- SHUNT LOSSES:** A shunt causes power losses by providing an alternate current path and short-circuiting a module or cell. Such a diversion causes significant heating of the affected component.
- MISMATCH LOSSES:** Mismatch losses are caused by the interconnection of solar cells or modules that do not have identical properties, or that experience different conditions from one another.
- REDUCED CURRENT LOSSES:** Reduced current losses are caused by soiling, shading, and degradation. They may reduce the current, but not necessarily the voltage. This measurement is particularly susceptible to human error, such as incorrect model inputs, irradiance sensor orientation, or transient weather conditions.
- REDUCED VOLTAGE LOSSES:** Reduced voltage losses are due to the increased temperature of the module, degradation, or the reduced contribution of a group of cells (e.g., due to shading), or due to a shorted bypass diode.

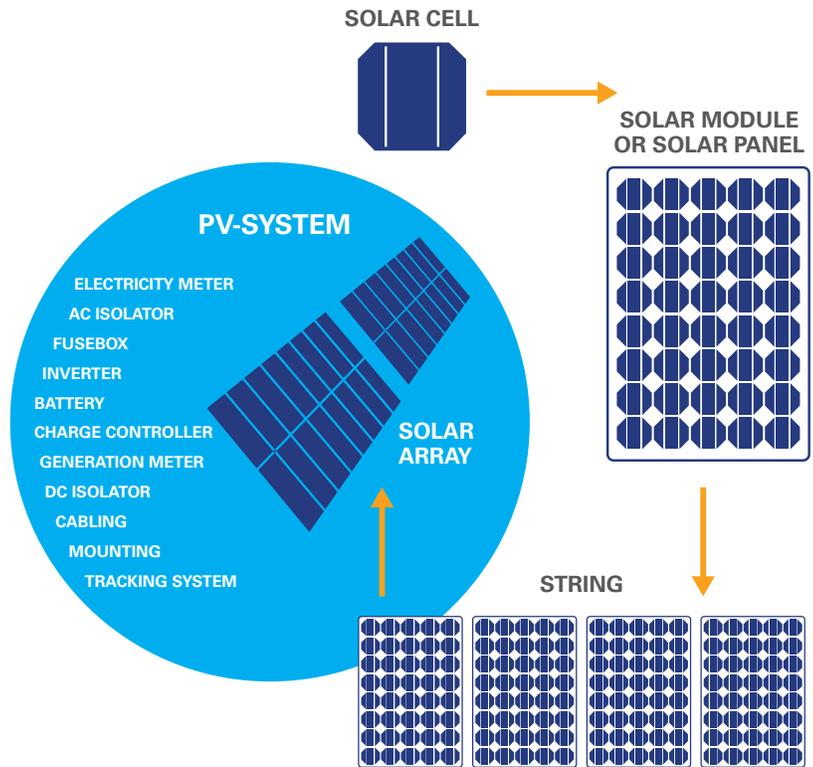


FIGURE 2: PV systems are built in a hierarchy, and cells and modules are the fundamental building blocks

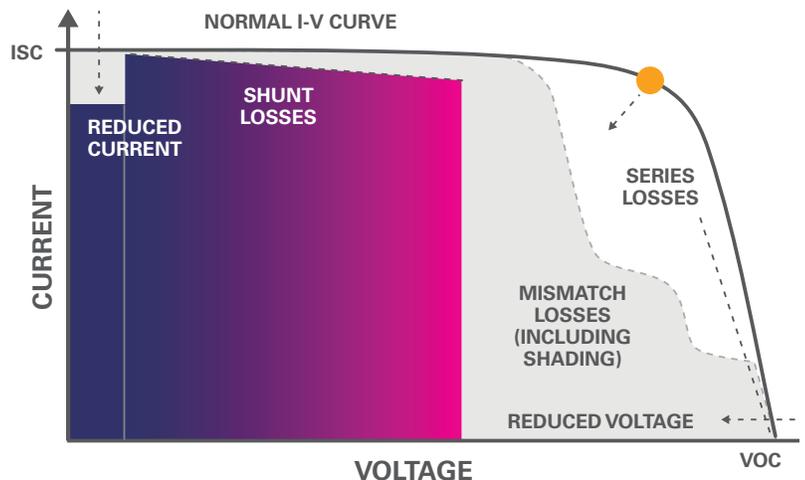


FIGURE 3: IV-Curve tracing is the industry standard for inspecting and evaluating performance of a solar array (Source: Hernday, Paul; Field Applications for I-V Curve Tracers)

HOW DRONE THERMAL IMAGING HELPS PV INSPECTIONS

To complement and enhance manual electrical testing, the use of drone thermal imaging for PV inspections, also known as aerial thermography, is increasingly required in contracts for PV system commissioning and maintenance due to the speed and level of detail that the technology package can provide. Whereas the manual inspection of a small PV system may take hours or days, a drone thermal imaging inspection of hundreds of acres, including panel cell-level defect analysis, can be accomplished in a single day.

Longwave infrared (LWIR) cameras, also known as thermal cameras, detect the infrared band of the electromagnetic spectrum, which allows them to “see” in total darkness and through obscurants such as fog and smoke, measure temperature, and accurately detect anomalies. Aerial thermal imaging cameras make it easy to quickly inspect a large target area and pinpoint solar panel problems. They streamline the completion of a qualitative analysis by allowing the operator to quickly see heat differentials across a solar field and identify possible impairments.

An aerial RGB (red green blue), or visible-light, camera helps detect non-electrical issues like soiling, shading, bird excrement, and animal nesting. A thermal-only payload could potentially lead to false positives by mis-identifying these same issues as electrical anomalies. Pairing thermal cameras with RGB cameras in a drone sensor suite provides both the required visible awareness and context to effectively and accurately spot anomalies in the field.

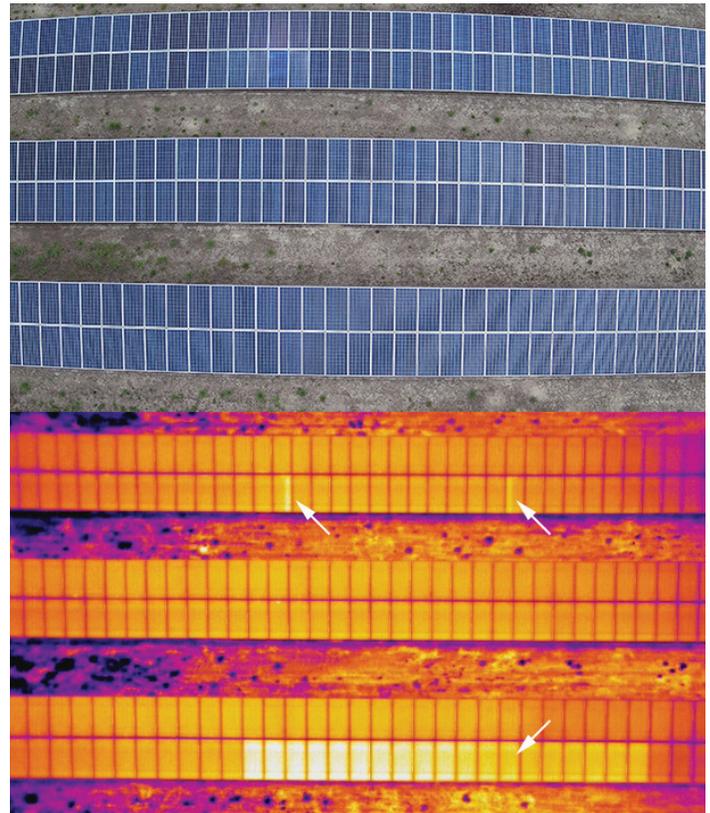


FIGURE 4: Aerial RGB (top) and thermal imagery (bottom) help detect and locate anomalies in the solar array, such as activated bypass diodes and offline strings. Captured by a dual sensor camera. Image provided by Raptor Maps.

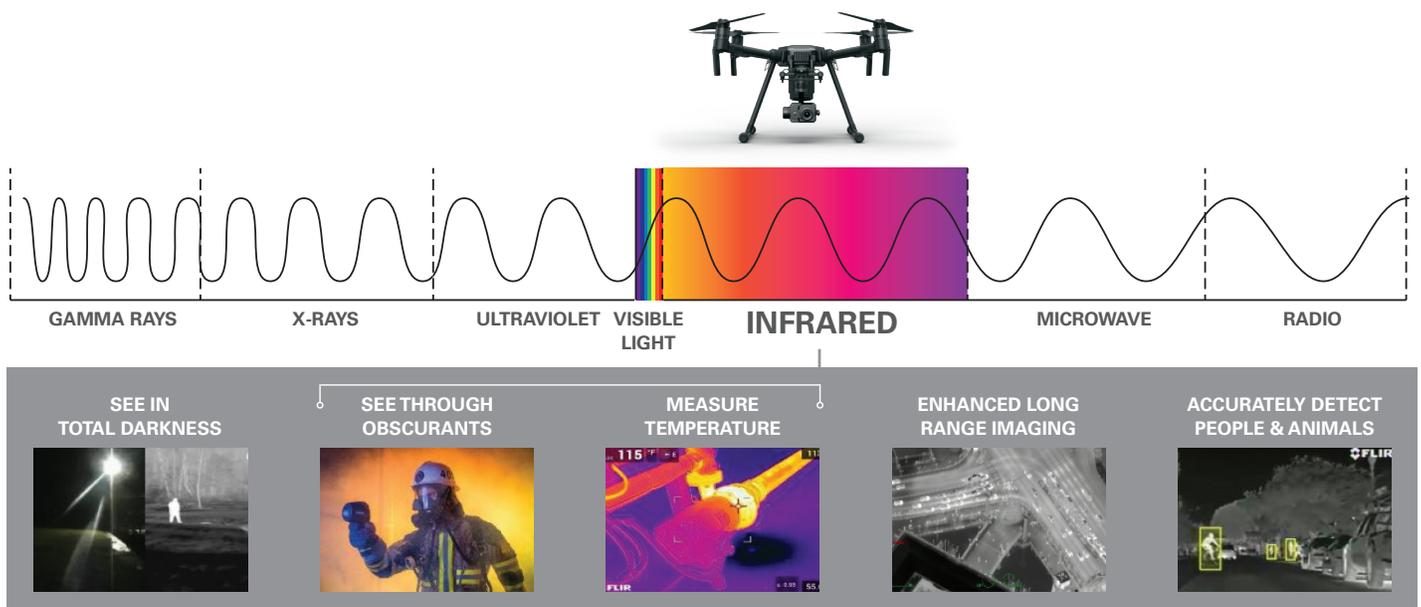


FIGURE 5: Thermal cameras detect and image longwave infrared energy

HOW TO USE DRONE THERMAL IMAGING FOR SOLAR INSPECTIONS

With the results of a professional drone inspection that combines thermal and RGB imaging data, a PV testing technician can more efficiently execute manual electrical testing on only the impaired PV panels. However, the practice does require as much, if not more, training than what is required for manual IV Curve Tracing.

PV inspections should include both quantitative and qualitative analysis paradigms. Qualitative analysis refers to what is seen during post analysis of the thermal and RGB images, such as a soiled or shattered module. Quantitative analysis refers to the temperature data from each pixel of the thermal sensor. Although each pixel of an RJPEG image contains temperature data, the actual temperature given by a thermal camera is an average of the data captured in a 10x10 pixel area. The operator must input the correct Measurement Parameters (emissivity, reflected apparent temperature, and atmosphere) in order to get an accurate temperature measurement. Radiometric, or temperature, data can provide additional diagnostic information that will better inform the manual IV Curve Tracing test.

Due to the additional training and specialized skills required, some solar asset owners and energy companies hire full-time internal aerial thermographers to handle drone inspections. However, it is more common for companies to outsource surveys to specialists with extensive backgrounds as drone pilots and thermographers. Either way, aerial thermographers must consider the following three factors while in the field and during post processing:

1. ENVIRONMENTAL CONDITIONS
2. HARDWARE CONSIDERATIONS
3. DATA ACCURACY

Environmental Conditions

The atmosphere allows infrared energy to transmit most of the radiation from a target object, but it is not 100 percent transparent. Humidity, wind, distance to the object of interest, air temperature, and other factors can affect thermal sensor performance and temperature measurement accuracy. Ideal conditions for a drone thermal imaging solar inspection are clear skies with low wind speeds. The thermal signature is most prominent on sun-heated PV panels.

Late morning to early afternoon is the optimal time to perform a drone-based thermal inspection. Condensed moisture accumulated overnight has evaporated and the scene has not yet to become isothermal. Isothermal scenes are caused by extended periods of steady temperatures (e.g., nighttime) and prolonged solar loading, both of which decrease the temperature differences between objects in the scene, making it more difficult to detect temperature anomalies.

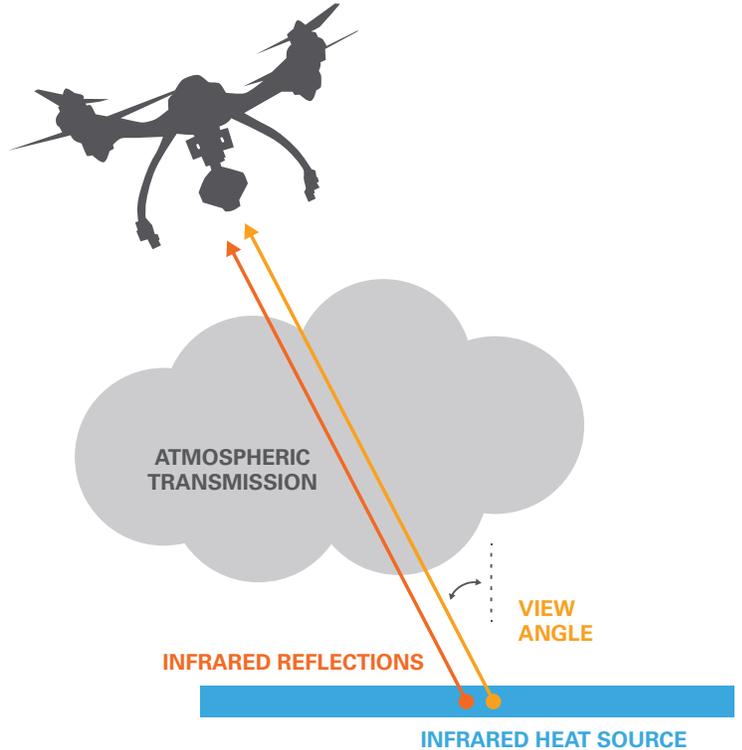


FIGURE 6: Environmental conditions affect thermal sensor performance and temperature measurement accuracy

Hardware Considerations

Not all drone thermal imaging systems are created equal. There are key parameters that make drone thermal imaging possible for solar inspections.

- **FLIGHT SPEED:** For large sites from 100 to 1,000 acres, the use of a fixed-wing or vertical takeoff and landing (VTOL) fixed-wing UAS allows for longer flight times, higher speeds, and an increase in overall coverage. However, higher flight speeds can lead to image blur and reduced quality of data, especially for those thermal cameras that have frame rates less than 30 Hz. It is important to use an efficient flight plan to minimize passes (time in the field) without compromising data quality.
- **INTEGRATION:** The use of dual sensors, both RGB and thermal, allows for redundancy and expanded situational awareness when determining possible anomalies in a PV system. Dual sensor systems decrease the amount of time in the field and lead to larger amounts of data that need to be stored and analyzed, but the value they provide is so significant that they are quickly becoming a requirement rather than an option.

- **RESOLUTION:** Camera resolution requirements are determined by the size of the object to be imaged, distance to the image, and the level of detail needed in the images. Drone thermal cameras applicable for solar field inspection are available in quarter visual graphic array (QVGA) 320x256 and VGA 640x512 resolutions. VGA resolution is recommended for PV system inspections.
- **FRAME RATE:** The frame rate is the rate at which the infrared detector creates images. For example, a 30 Hz camera does so 30 times per second. If the LCD/viewfinder has a higher display rate, the infrared image repeats a number of times until the camera provides the updated image. A frame rate of 30 Hz or higher is recommended for PV system inspections.
- **RADIOMETRIC CAPABILITY:** All thermal cameras can provide an image of the relative intensities of thermal energy within their fields of view, but some cameras take that a step further and provide calibrated, non-contact temperature measurements of those objects. This is a process called radiometry. Radiometric thermal cameras are adequate for anomaly detection, but radiometric thermal cameras provide additional data and are becoming more widely used for PV system inspections.
- **LENS:** Depending on the lens size, infrared camera systems can detect human-sized objects up to several kilometers away. As the object that needs to be detected decreases in size, the maximum detection range also decreases. A 13 mm focal-length lens is optimal for thermal drone inspections of solar fields.



FIGURE 7: Drone camera include RGB, thermal or a combination of both cameras

| INSPECTION TYPE | OVERVIEW | STANDARD | COMPREHENSIVE |
|--|--|--|---|
| Description | Ideal for rapid drone flights and string-level outages | Ideal for annual preventative maintenance | Meets IEC TS 62446-3 thermography standards |
| Smallest visible features | Module | Diode, Hot Spot, and Cell | Absolute Temperature Accuracy |
| Thermal ground sample distance (GSD) | 5.9 ± 2.0 in/pixel (15.0 ± 5.0 cm/pixel) | 2.2 ± 0.2 in/pixel (5.5 ± 0.5 cm/pixel) | 1.2 ± 0.2 in/pixel (3.0 ± 0.5 cm/pixel) |
| Altitude required with 640x512 thermal camera (13 mm lens) | 380 ± 126 ft (116 ± 38.5 m) | 140 ± 12 ft (42.5 ± 3.5 m) | 76 ± 12 ft (23 ± 3.5 m) |

FIGURE 8: Thermal-camera resolution is a key consideration when determining solar array inspections flight planning. Note that the smallest distinguishable feature will be larger than the GSD.

DATA ACCURACY

While working with the Geographic Information Systems (GIS) team and chief surveyor, a standard ground sampling distance (GSD) will be determined, which is the benchmark for preparing flight operations. Comprehensive inspections require a 3 cm thermal GSD while a high-level overview can be done at a 15 cm thermal GSD.

An object’s thermal-camera-measured temperature results from a combination of emitted, transmitted, and reflected radiation. In thermography, aerial or otherwise, emissivity is the single most important attribute necessary for accurate thermal measurement. It’s influenced by material, surface structure, geometry, angle, and temperature.

Emissivity is the ratio of the actual amount of electromagnetic radiation emitted by an object to the amount emitted by an ideal blackbody at the same temperature. A blackbody is a perfect absorber and emitter and has an emissivity value of 1. Solar panels tend to be highly reflective, which means a lower emissivity and an increased challenge in measuring highly accurate temperatures. It is important to set the correct emissivity value in the thermal camera to get an accurate temperature reading. Many thermal cameras have predefined emissivity settings for specific materials. If predefined settings are not applicable, then thermographers must rely on publicly available emissivity tables.

Beyond emissivity, data accuracy may also be influenced by post processing. Post processing data captured during an inspection using advanced software provides time and temperature plots, detailed comparisons of impaired PV panels versus properly running PV panels to emphasize anomalies, high-resolution zooming, and much more. The software should preserve the original radiometric pixel values and not introduce errors from blending or stitching images.

There are three metrics that no amount of post processing can ever fix: focus, range, and distance (FORD). Out-of-focus thermal images are not reliable. Range refers to the correct temperature

range being set on the thermal camera. Distance refers to the appropriate working distance from the object being imaged. Flaws to FORD will likely result in inaccurate data.

Isotherms highlight dedicated temperature ranges and should be available in the settings of the ground control station software. Anything that appears outside of a certain temperature range raises a visual red flag so a thermographer can zoom in on the issue. When used correctly, isotherms can eliminate hours of post-processing analysis.

WHAT TO LOOK FOR IN A DRONE SERVICE PROVIDER (DSP)

Drone pilots provide a variety of services, from construction site security to aerial cinematography. For solar field inspections, there are some minimum qualifications that a DSP must meet to ensure safe operations and quality data.

Regulations and Certifications

The unmanned aircraft system (UAS) commercial industry has rapidly matured since August 2016, when the first commercial drone regulations were passed by the FAA. To become a certified, Part 107 commercial UAS pilot, a pilot must pass a 60-question multiple choice exam.

To ensure safety and compliance, the entire flight crew should be FAA Part 107 certified, at a minimum. DSPs need to be familiar with the local FAA Flight Safety District Office (FSDO) and know when to engage Air Traffic Control (ATC), such as when attempting to survey beyond visual line of sight (BVLOS) or flying in controlled airspace. If the operation calls for flight parameters that are outside of the current regulatory framework, DSPs need proof of FAA waivers.

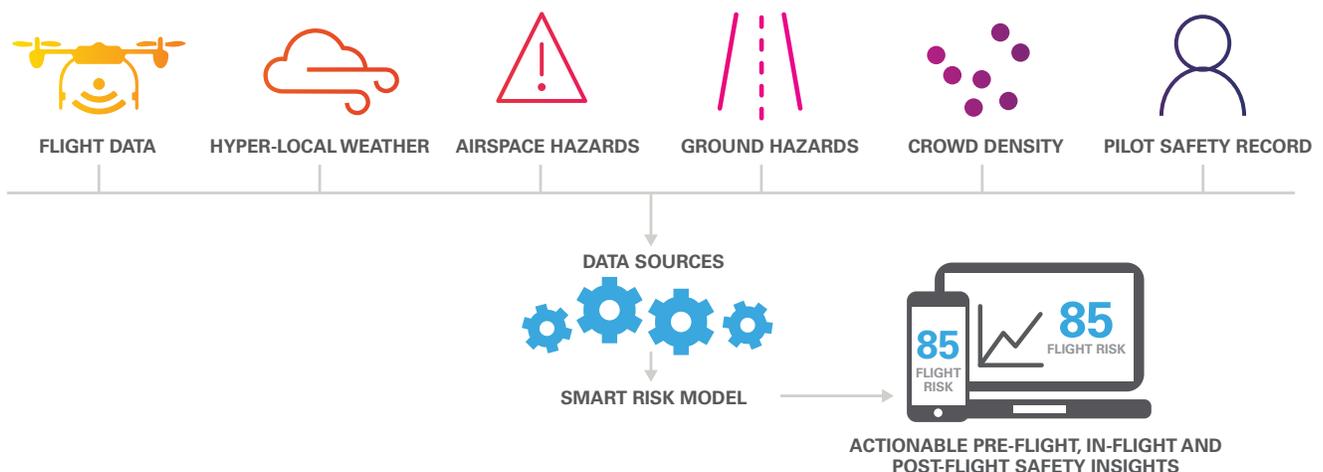


FIGURE 9: Drone flight insurance considers key information to determine risk

For detailed quantitative analysis, a certified thermographer needs to ensure that the data produced is accurate and therefore useful to the task at hand.

Insurance

As the value of solar assets being inspected increases, it is important to consider the proper insurance before hiring a DSP or establishing an in-house program. Ensure the pilot has a UAS-specific aviation insurance plan with a minimum of \$1 million to \$5 million in coverage. New, on-demand insurance apps could be a good option if a given program is young and the volume of flights on a monthly basis is minimal. If the assets to be inspected are on residential homes and urban areas, more precautions should be taken when purchasing an insurance policy. For remote, rural operations with limited risk, the on-demand option may be viable.

Experience

One of the most mission-critical items to consider when hiring a DSP is experience. In a new and fast-paced industry, clearly showcasing experience can be difficult. Completing a strict due diligence process prior to decision making will set up asset owners and energy stakeholders for long-term success while managing risk for hiring pilots and/or thermographers, whether outsourced or within an organization. A few items found in all due diligence protocols include:

- FLIGHT LOGS AND A MAINTENANCE SCHEDULE
- DATA WORKFLOW DETAILS
- PRE-FLIGHT, DURING FLIGHT, AND POST-FLIGHT CHECKLISTS
- SAMPLE DATA SETS (PROOF OF ABILITY)

To set up an internal drone program for success, participants should be certified pilots, thermographers, or both.

Software

Whether choosing a PV inspection DSP or developing an in-house program, choosing the correct data analysis software is crucial to data accuracy and long-term monitoring. Capabilities for data collection, processing, and analysis; localization of anomalies; and reporting will define costs and efficiencies of a digital inspection process. Consulting with IT and GIS professionals represents a good place to start when considering software for a given PV inspection drone program. Current software capabilities provide more detail and allow for a deeper level of accuracy than what can be achieved manually.

Detailed Deliverables

There are numerous software choices available in the market but starting with an organization’s expectations and working backwards will make the final deliverable much clearer. Questions to consider when developing a deliverable strategy include:

- WHAT FORMAT (CSV, PDF, WORD, ETC.) WILL THE REPORT BE IN?
- IS DATA ACCESSIBLE VIA AN ONLINE, CLOUD-BASED SYSTEM?
- IS DATA EDITABLE AND CUSTOMIZABLE?
- IS THERE ACCESS TO THE RAW DATA FILES (EXPORT AND API ACCESS)?
- IS THE DATA SHARABLE ACROSS THE ORGANIZATION?
- DO THE NAMING CONVENTIONS MATCH THE CLIENT’S ASSET DATABASE?
- WILL THE OUTPUT INCLUDE AN ANOMALY MAP OF THE INSPECTION SITE TO LOCALIZE IMPAIRED PANELS AND SIMPLIFY GROUNDWORK FOR FIELD PV TESTING TECHNICIANS?

By providing detailed yet flexible deliverables, the end user can take advantage of actionable insights produced by the reporting software.

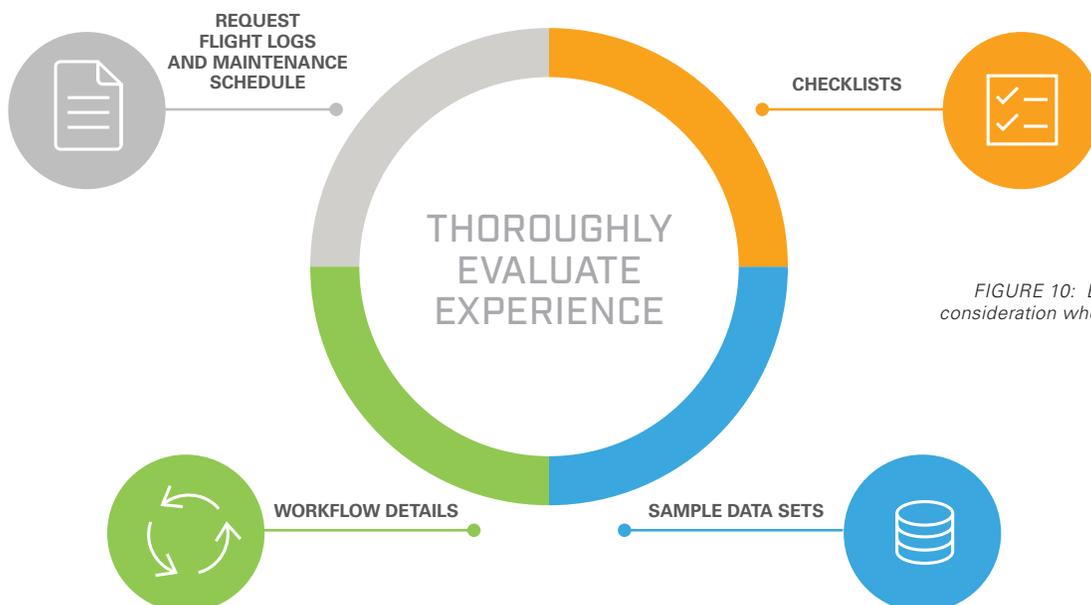


FIGURE 10: Experience is a key consideration when selecting a DSP

Timelines

While conducting due diligence, discussing timelines will ensure projects do not run over schedule or budget. Often, the return on investment (ROI) is viewed as time saved and efficiency, so it is critical to understand up front how long the process will take. Drone PV inspection strategies need to incorporate the following, at minimum:

- START TIME AND FLIGHT SCHEDULE
- DURATION OF FLIGHT
- DATA PROCESSING TIME
- BAD WEATHER PLAN
- EXTRA FLIGHTS
- FINAL REPORT DELIVERABLE TIMELINE

LIMITATIONS OF THERMAL IMAGING FOR PV INSPECTIONS

While drone thermal imaging is revolutionizing PV inspections, it is important to understand the maturity of the industry and where the current state of end-user integration lies. Market adoption starts with education and a firm grasp of the limitations of the technology will set a standard for success.

Camera Limitations

Camera resolution is driven by multiple inputs, including the desired ground sampling distance (GSD). When looking for cell or sub-cell anomalies requiring 3 cm GSD, a higher resolution VGA camera is necessary along with lower flight altitude and, potentially, a lens with a narrower field of view (FOV). For high-level analysis of issues such as string or tracker defects

that require a 15 cm GSD, the thermal camera can be a lower resolution and/or the flight altitude can potentially be elevated.

For PV inspections, video is not the best medium for analysis because of:

- LOW QUALITY
- STORAGE PROBLEMS
- RADIOMETRIC ANALYSIS NOT POSSIBLE
- INCORRECT IDENTIFICATION OF ANOMALIES
- GEOTAGGING NOT POSSIBLE

Also, thermal zoom is a technology yet to be perfected on light drone aircraft. For pilots flying a dual EO/IR sensor, only the visible or RGB (also known as color, electro-optical, or EO) camera will have in-flight zoom capability.

Environmental Limitations

Environmental limitations include atmospheric transmission, air density, relative humidity, moisture, clouds, and high winds. Under less than ideal conditions, these factors need to be accounted for in the camera settings during pre-flight preparations. Not only can wind and moisture negatively affect flight operations, it can also create issues with irradiance and data capture. Moisture could potentially make the panels look uniform or isothermal, which could ultimately lead to overlooking impaired panels. And cloud cover and other adverse environmental conditions could affect the image that the thermal camera is attempting to capture.

Irradiance and Operating Status

Irradiance is the density of radiation incident on a given surface usually expressed in watts per square centimeter or square meter. PV cells must reach a certain level of natural irradiance to get a true apparent temperature reading. The ideal irradiance to perform an inspection is 600 W/m². Airborne thermal inspections can be completed at other irradiance levels, but may result in lower quality data.

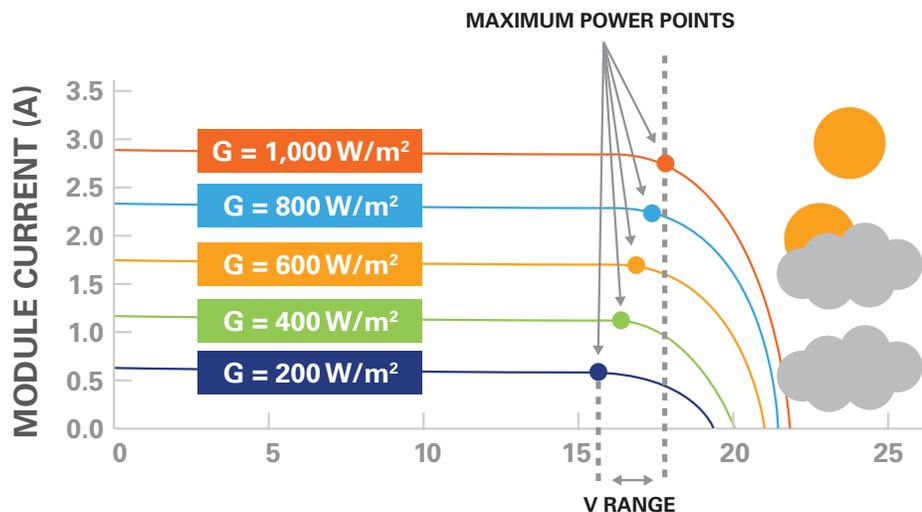


FIGURE 11: Environmental conditions impact irradiance (Source: EC&M Magazine)

Coverage and Flight Times

Based on the hardware, software, and size of the area to be inspected, the coverage area and flight times will vary. With keeping the end deliverable and goal in mind, the following requirements will contribute to the amount of coverage that can be achieved:

- ALTITUDE
- OVERLAP
- FLIGHT SPEED
- GSD
- ENVIRONMENTAL CONDITIONS

Using multiple drones can maximize coverage and minimize flight times.

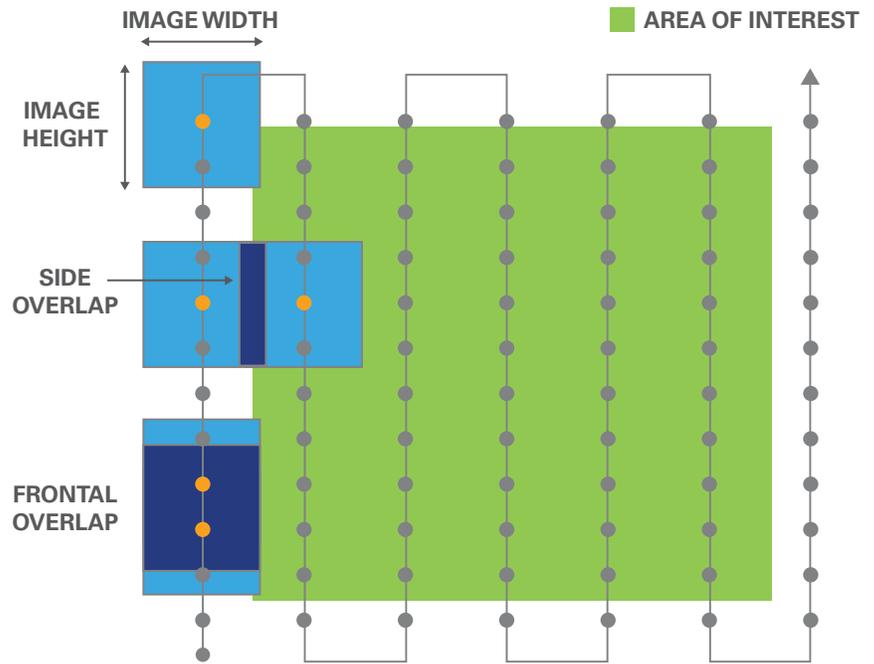


FIGURE 12: Flight planning requires several inputs to achieve complete coverage

CONCLUSION

As countries, states, and cities begin to increase the production and utilization of solar panels for renewable energy, the need to inspect and maintain these critical assets will become vital to managing costs and efficiency. The rise in drone technology is proving to be a crucial tool for inspecting both small and large solar fields alike. As thermal sensor, software, and platform technology continues to evolve, so will the techniques to collect

and process thermal data, making it easier to ensure compatibility with workflows and company procedures. As thermal drone solar inspections become more mainstream, asset owners and energy companies will need to determine whether outsourcing or developing in-house programs makes the most sense for their long-term goals.

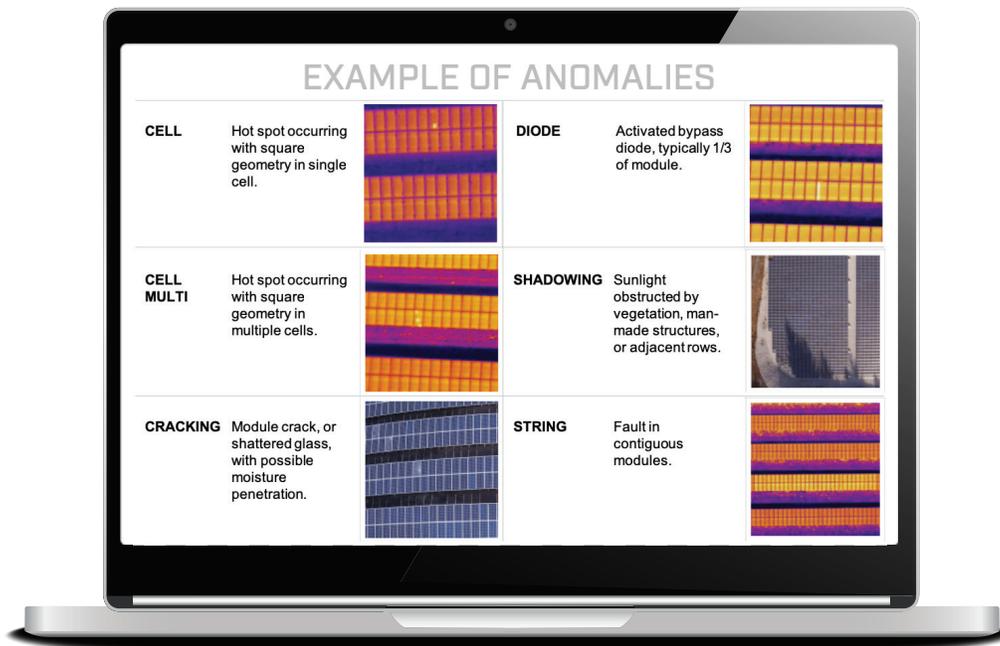


FIGURE 13: Thermal drones can help improve efficiency of solar-array inspections. Example images provided by Raptor Maps.

For more information about thermal drone cameras,
please visit www.flir.com/suas

For more information about thermal drone knowledge, best practices,
training and street truths, please visit www.flir.com/delta

*The images displayed may not be representative of the actual resolution of the
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