A Snapshot of an Emerging Industry: Aerial Inspections of Utility Scale Solar Plants

UCLA Institute of the Environment and Sustainability

Senior Practicum Project

UCLA
Institute of the Environment and Sustainability

Authors:

Laurence Ng-Cordell

Nour Abou Fadel

Huong Le

Wentao Wu

David Zeng

Lilian Wherry

Advisor:

Peter Kareiva

Published: August 2018

Table of Contents

Solar continues to grow and evolve

From 2010 to 2017, solar increased its share of total U.S. energy generation from 0.1% to 2%.[1] In 2017, utility scale solar represented 59% of newly installed energy generation capacity in the country.[1] There are now 32.4 GW of operational utility scale solar, 19.3 GW either contracted (Power Purchase Agreement (PPA) signed) or under construction, and 30.1 GW announced but not yet contracted.[1]

"Most analysts are too conservative in their forecasts … We expect yearly installations to hit 100 GW in the next few years"

– Managing Partner of Capitas Energy

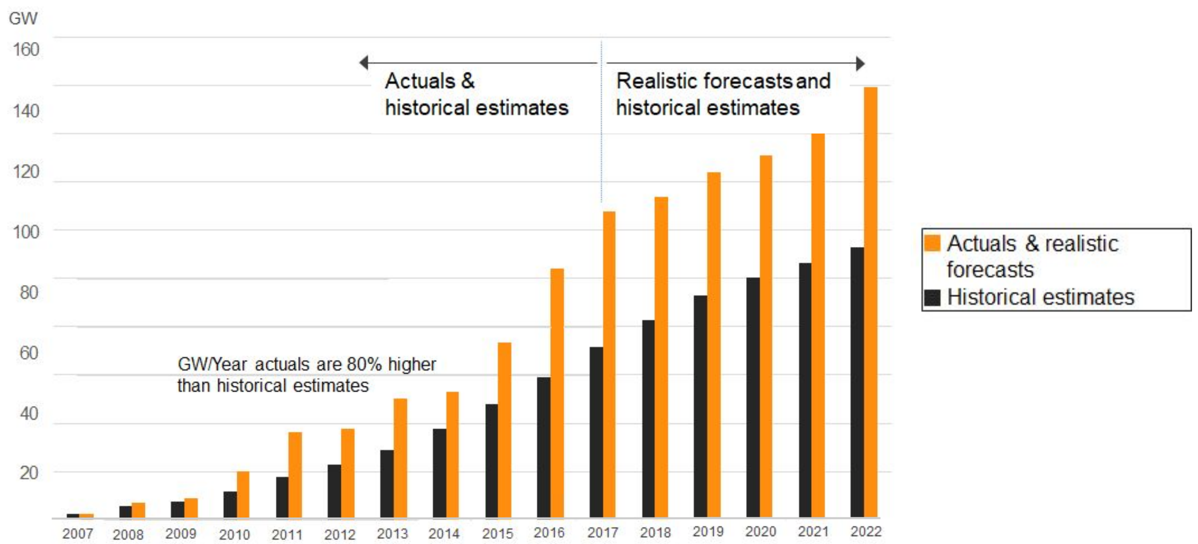


Figure 1: Yearly solar installations: historical estimates, actuals, and current forecasts (conservative and realistic)[2]

The primary economic drivers behind solar's tremendous growth have been tax credits and falling installation costs.[1]

Figure 2: U.S. Solar Installations driven by Investment Tax Credits (ITC) [1]

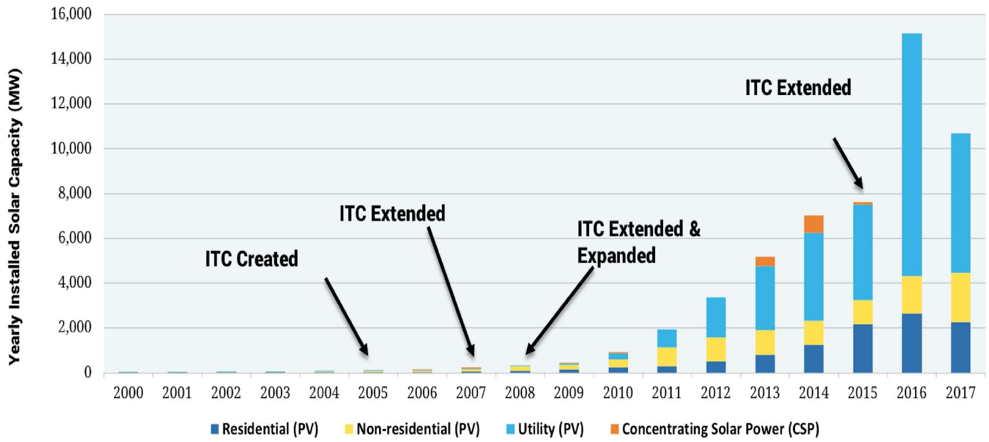
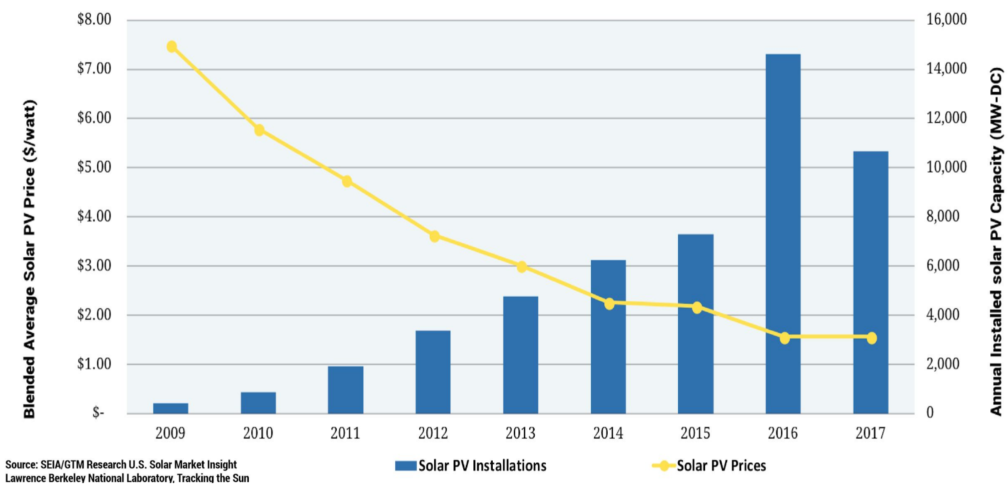
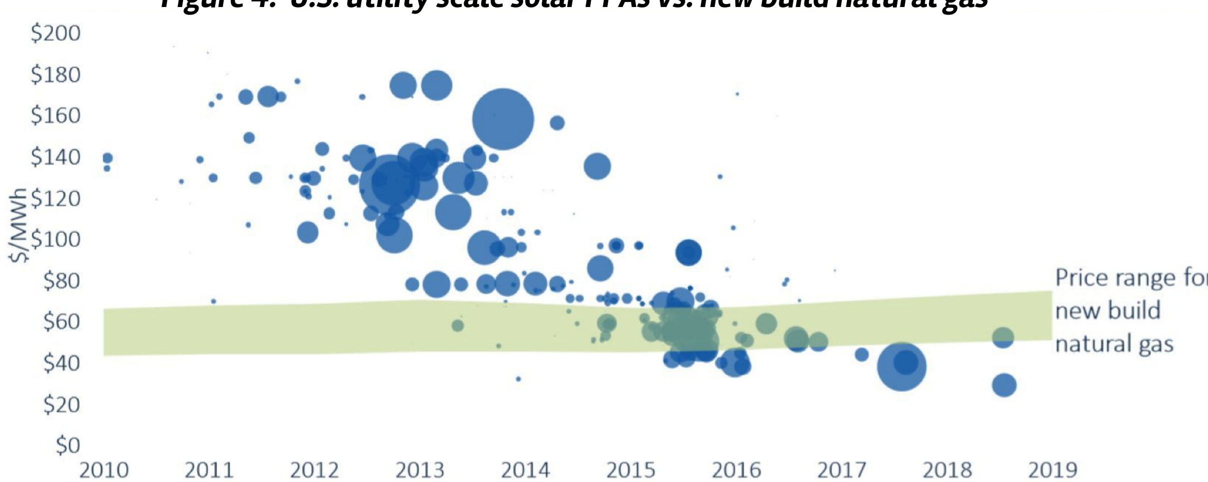


Figure 3: U.S. solar growth driven by falling installation costs [1]



Although tax credits and the decreases in installation costs are tapering off, solar has reached grid parity in 27 states (compared to only 12 in 2014).[1] Nevertheless, PPA prices continue to decrease, and utility scale solar is pressed for further cost reductions.[2,3]

Figure 4: U.S. utility scale solar PPAs vs. new build natural gas [3]



Greater focus on soft costs

- Although hardware and "soft" costs have both decreased, soft costs have become a greater part of total system costs.[4]
- Future cost-reductions will mostly come from soft costs.[4]
- Major soft costs include customer acquisition costs, permitting processes, as well as operations and maintenance (O&M).[1]
- While the Department of Energy, SEIA, and The Solar Foundation are working with cities and counties to streamline permitting processes, plant owners and operators are looking to aerial inspections to cut O&M costs.[1]
- This report will describe the relative value of aerial inspection services and the provide a snapshot of this new and rapidly growing sector in the solar industry.

Overview: current inspection and monitoring practices

Method	What is it?	Detail of Inspection	Relative Cost
Manual Inspections	● Visual inspection ● IV-curve tracing: directly measure current & voltage ● Taking photos with a handheld thermal camera ● Engineer interprets the data	○ Reveals more than any other inspection method ○ Detects internal and external faults such as soiling, blown fuses, inverter failures	$$$ (dangerous → liability costs)
Monitoring Systems (SCADA)	● Real-time measurements by fixed instruments: current, voltage, power, irradiance, ambient temperature, wind speed and direction ● Software analyses performance; data displayed in control rooms; staff make maintenance decisions	○ Resolution varies: faults detected at combiner-box level, or at inverter level ○ If substantial reductions in power output are detected, engineers are dispatched to manually determine where and what the problems are	$$$$$
Aerial Inspections	● Manned aircraft or remotely piloted rotor-blade drones ● Quickly capture visual & thermal images of the entire plant ● Post-inspection or near-real time analysis (~50 minute delay) ● Produce actionable reports	○ Classify and locate internal and external defects at micro- and macro-level faults ○ Estimate power output loss ○ Localize manual inspection orders ○ Guide maintenance decisions	$ - $$

Aerial inspections excel where manual inspections and monitoring systems struggle:

- ➢ Manual inspections of entire plants are not effective
- ➢ Monitoring systems fail to capture small yet incrementally significant problems
- ➢ Aerial inspections can survey entire plants effectively and guide further maintenance decisions

Manual inspections of entire plants are not effective

Although manual inspections ultimately provide the most detailed analysis, labor-intensity limits their effectiveness for plant-wide inspections and the sheer size of the task leaves significant scope for human error.

Monitoring systems fail to capture small yet incrementally significant problems

Monitoring systems provide valuable real-time performance data but lack granularity. This becomes problematic when small and high-risk or cheap-to-fix problems go undetected.

For example, if one string were completely offline due to a blown fuse, a monitoring system measuring at the combiner-box level (e.g. monitoring power output from 16 strings) may not prompt an inspection of this region because the noted reduction in output would be relatively small, and any repairs may not yield sufficient returns due to the potentially high cost of locating and repairing the problem. However, if it was known that the reduction in power was caused by a blown fuse at a specific location, it would be straightforward and cost-effective to replace the fuse.

Over-reliance on monitoring systems can lead to missed opportunities for low-cost and financially worthwhile repairs.

Aerial inspections survey entire plants effectively and guide further maintenance decisions

Aerial inspections classify and localize faults quickly and cost-effectively. Since leading aerial inspection firms claim >90% field identification, engineers dispatched to problem areas are much more likely to arrive equipped to fix the problem.

Poor inspection practices are prevalent

Focused on cutting O&M costs, some plants have adopted ineffective inspection practices:

- ➢ Conducting annual inspections only to meet PPA requirements
- ➢ Cutting inspection frequencies due to high inspection costs
- ➢ Performing inspections reactively
- ➢ Inspecting "representative samples"

Poor inspection practices can end up costing more than they save.

Conducting annual inspections only to meet PPA requirements

Among plants that conduct routine plant-wide inspections, most only do so annually. Perhaps coincidentally, annual inspections are typically required by PPA contracts.

Cutting inspection frequencies due to high inspection costs

Out of the plants we surveyed that do conduct routine plant-wide inspections (52.4%), less than half of those conduct plant-wide inspections more than once a year.

Performing inspections reactively

Typically, the plants we surveyed conducted plant-wide inspections only in response to substantial performance losses, such as those detected by monitoring systems.

Almost half of the firms surveyed conducted plant-wide inspections only in response to large reductions in power output. Performance issues are left until they have substantially developed.

Inspecting "representative samples"

High inspection costs not only deter frequent and routine inspections, they also lead some firms to opt for inspections of "representative samples" of their plants. Questionably, data from such inspections are used to guess whether other parts of the plant have defects.

"Since we have monitoring systems in place ... we only send a team out when we notice significant losses ... and most of the time we only do it to meet PPA requirements"

– Solar Plant O&M Coordinator

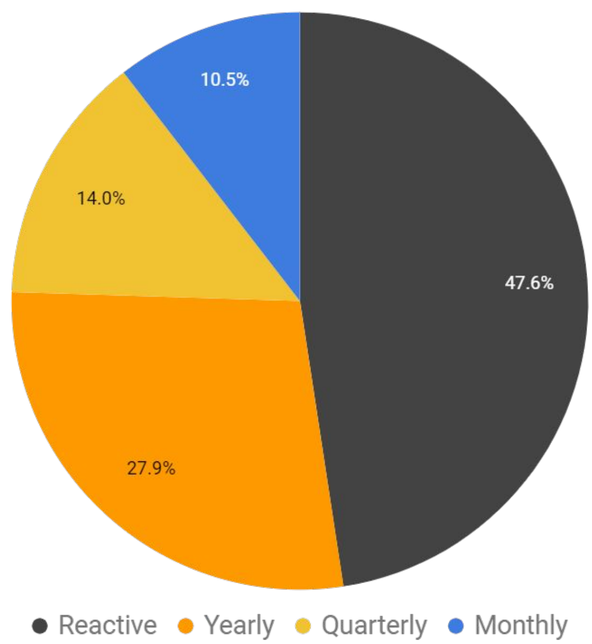


Figure 5: Solar plant field-inspection frequency (N.B. these yearly, quarterly and monthly inspections were plant-wide)

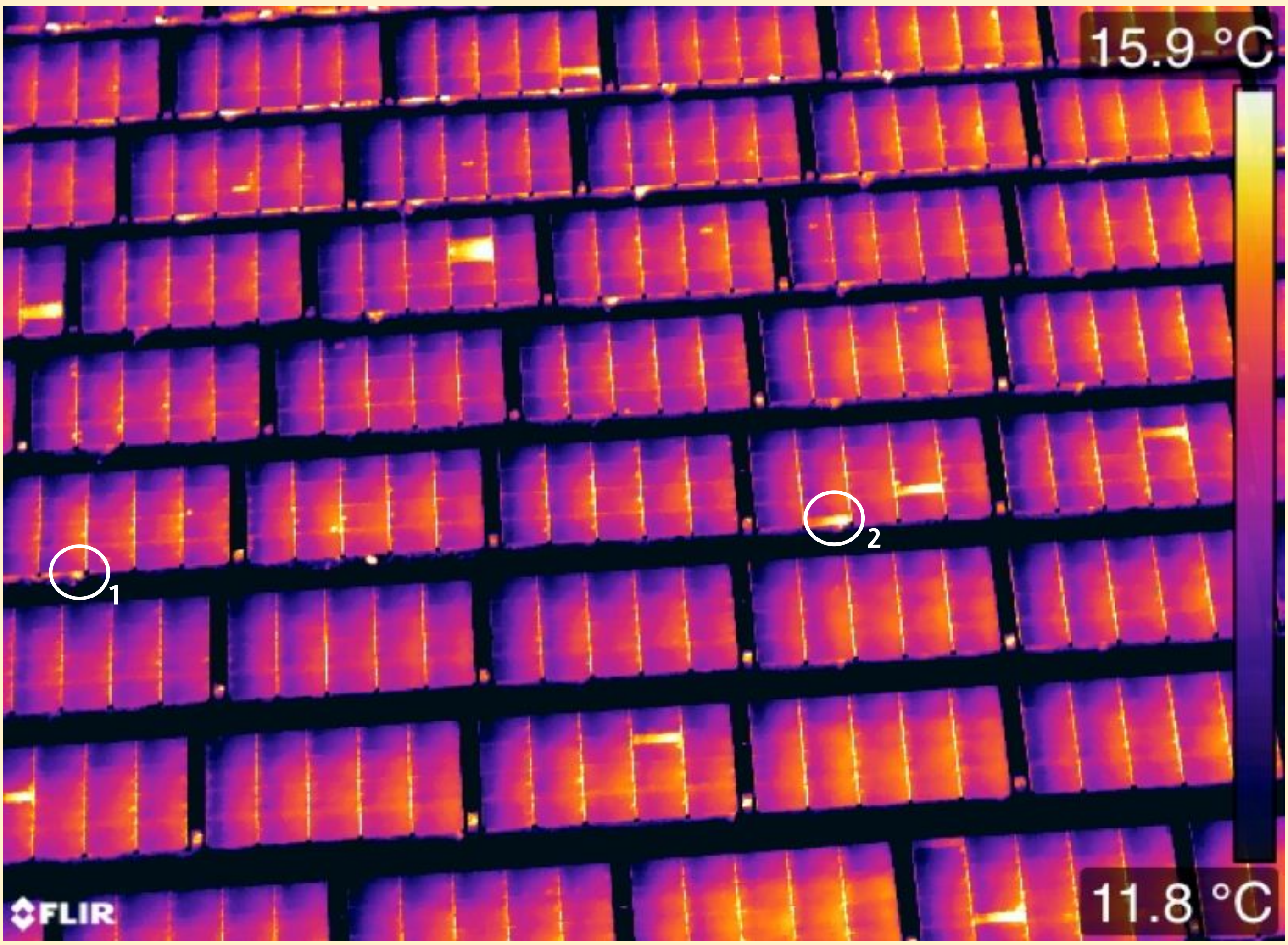
Poor inspection practices can end up costing more than they save

Small faults can develop into bigger faults. Fixes that were once cheap and easy often become costly and complicated. Blindly allowing problems to fester is a high-risk O&M strategy.

Box 1: The Overheating Epidemic

Thermal imaging reveals system components that are overheating. "Hotspots" are symptomatic of a variety of faults such as shading, defective cells, blown-fuses, and inverter failures. Hotspots act as heat-sinks, drawing energy from neighboring cells, and reduce module efficiency by ~0.5% per degree above optimal temperature.

Left unresolved, hotspots will develop as heat conducts to neighboring components because sustained overheating damages electrical circuits.



Hotspots 1 and 2 were caused by the same problem: tall grass casting a shadow over the bottom of the table. Whereas hotspot 1 reduced module output by 15 W, hotspot 2 reduced module output by 50 W. Hotspot 2 would have started life similar to hotspot 1, but since the root-cause of its overheating was not addressed (i.e. the grass was not cut), destructive overheating gradually spread to neighboring cells, eventually affecting the entire panel. Whereas hotspot 1 was fixed by simply cutting some grass, hotspot 2 had to be fixed by module replacement because cell degradation had spread throughout the panel.

Aerial inspections can cut O&M costs

Established and improving merits of aerial inspection services:

- Geo-referenced faults; visual, radiometric and financial analyses
- Faster and typically cheaper
- Accurate fault detection set to improve amid a robotic revolution driven by sensor improvements
- Accuracy will improve with “big”-er data, pattern recognition and machine learning

Geo-referenced faults; visual, radiometric and financial analyses

Aerial inspections fall into two categories: fixed-wing aircraft or rotor-blade drones. Both types capture geo-referenced visual and thermal images that are used to identify internal and external defects.

Visual analysis detects vegetation growth, panel soiling and physical defects such as cracks and panel/tracker mis-alignment. Radiometric analysis can provide root-cause analyses of more than 300 internal faults. Aerial inspection providers produce actionable reports that classify faults. Leading inspection providers also perform detailed financial analysis (e.g. performance loss calculations; ideal time to fix defects).

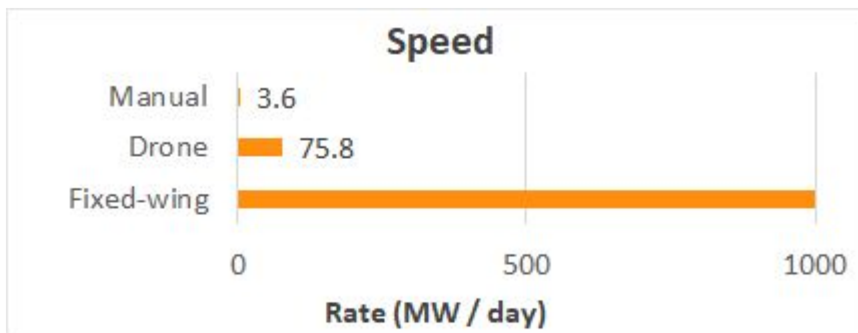
Faster and typically cheaper

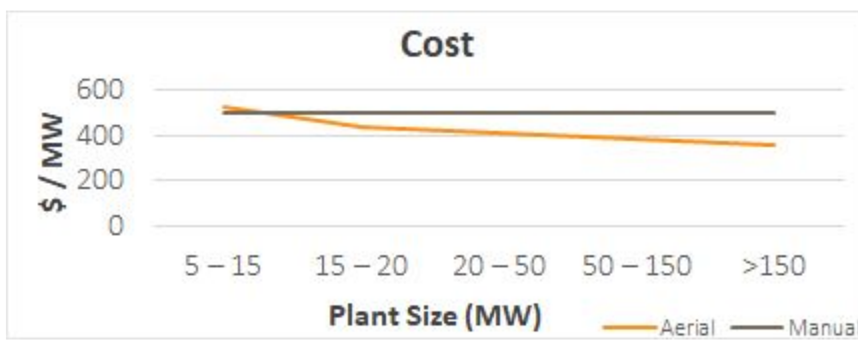
Aerial inspections are significantly faster than manual inspections. Faster inspections enable swifter maintenance which can reduce losses that would otherwise accumulate over time.

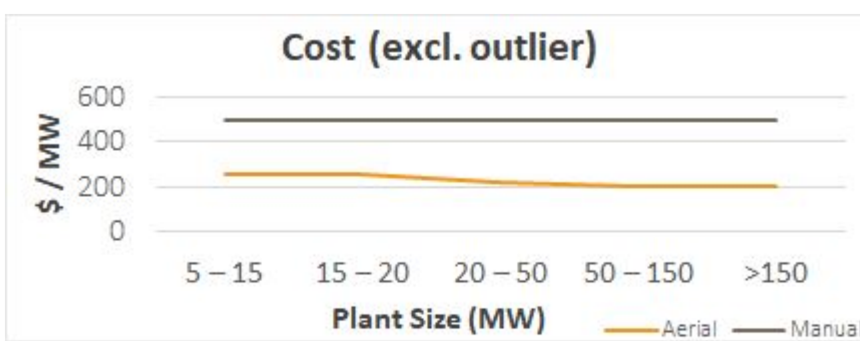
Prices per inspected MW range from $161-800, with considerable variation between various service providers and plant sizes. Nevertheless, our research suggests that aerial inspections are generally cheaper than manual inspections.

Not accounted for in this comparison:

1) aerial inspections typically engender further investigation, which is always performed manually;
2) oftentimes there is a transition period when both manual and aerial inspections are performed; thus, aerial inspections may be perceived as an additional cost.







Figures 6, 7, 8: Comparison of various inspection speeds and costs (N.B. compared against lowest manual inspection cost)

Accurate fault detection set to improve amid a robotic revolution driven by sensor enhancement

Increasingly high-resolution imaging sensors enable highly accurate fault detection. Current sensors can detect sub-cell level faults, but sensor technology will drastically improve (chip-stacking and better infrared sensitivity) as the industry keeps growing.

Sub-cell level resolution (of visual and thermal images) enables aerial inspection providers to predict fault development before faults compromise performance. This gives staff more time to plan and act accordingly.

Figure 9 : Sensor market size forecast by technology [5]

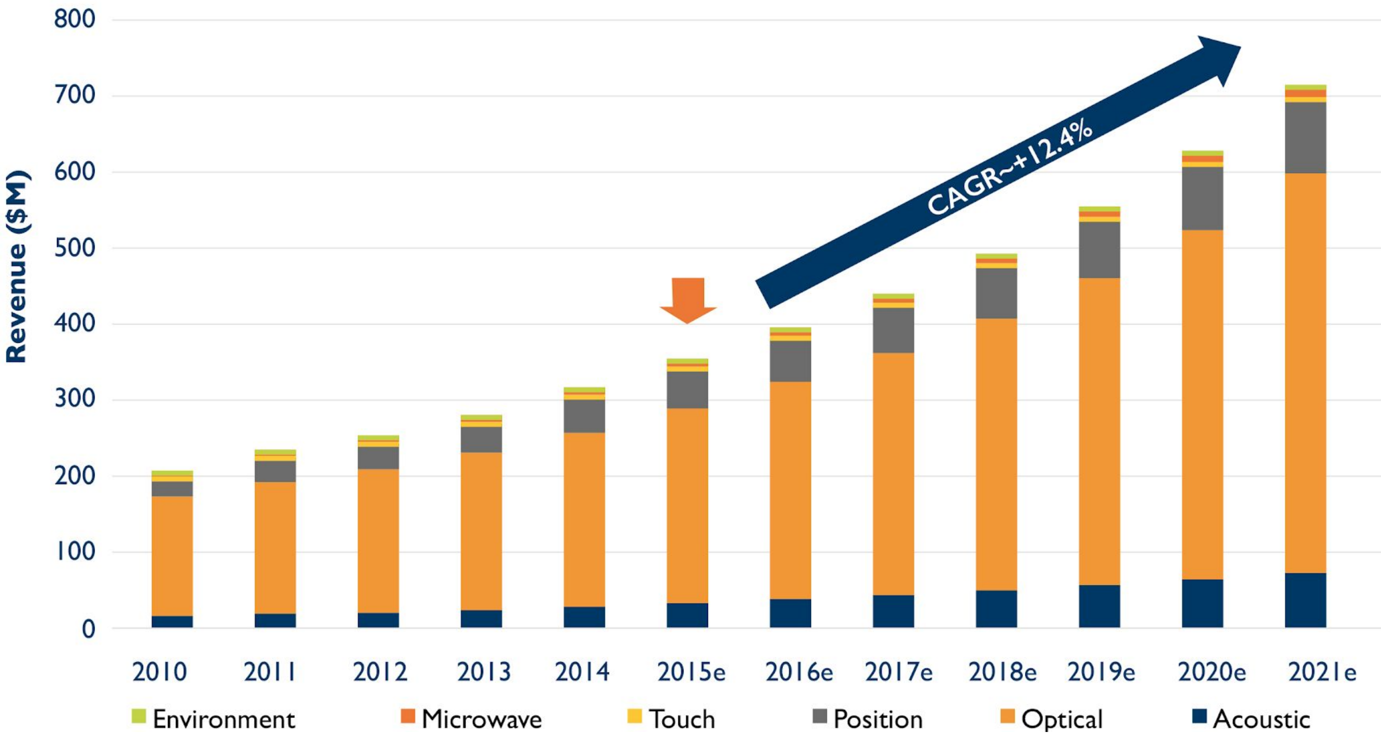
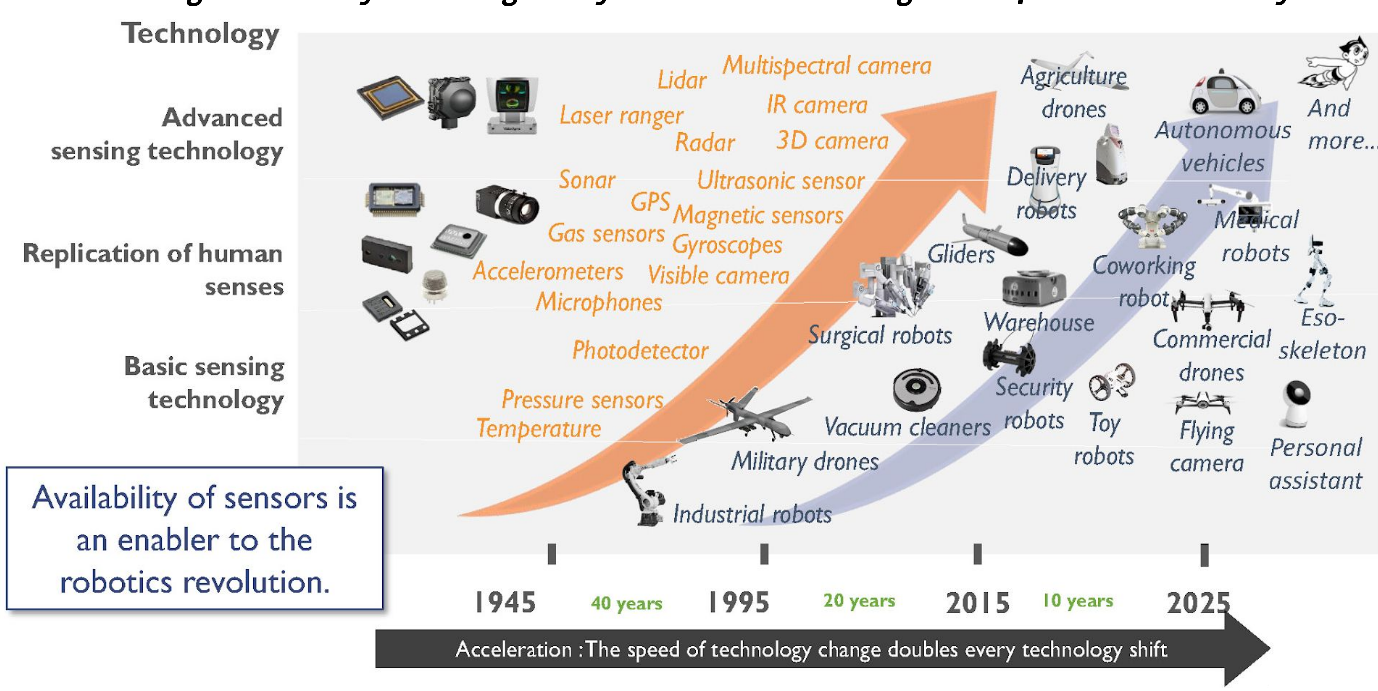


Figure 10: Many technologies rely on sensors and drive growth of the sensor industry [5]



Accuracy will improve with “big”-er data, pattern recognition and machine learning

Artificial intelligence (AI) goes hand-in-hand with aerial inspection services because each inspection generates vast amounts of imaging data. AI enhances the precision of fault identifications and classifications through pattern recognition and machine learning software. The larger the data bank, the more AI can improve fault classifications.

In addition to these intrinsic merits, aerial inspections enable the necessary shift to predictive maintenance:

- ➢ Aerial inspections optimize preventative maintenance while allowing for predictive maintenance
- ➢ Predictive maintenance informs plant operators how faults will likely develop, enabling staff to make smarter maintenance decisions
- ➢ Predictive maintenance improves inventory management and project cash flow

Aerial inspections optimize preventative maintenance while allowing for predictive maintenance

Aerial inspections optimize preventative maintenance by reducing inspection times. This minimizes losses that accrue either between routine inspections or before monitoring systems flag areas with significantly reduced output.

Predictive maintenance addresses significant performance issues before they materialize. High accuracy and precision allows aerial inspections to predict fault development. Low-granularity monitoring systems, laborious IV-curve tracing and manual-thermography are not suitable for predictive maintenance.

Preventative Maintenance	**Predictive Maintenance**
Triggered by time, events, meter readings	Triggered by actual condition of equipment
Scheduled maintenance/repairs	Identify failures before they develop (and repair them if necessary)

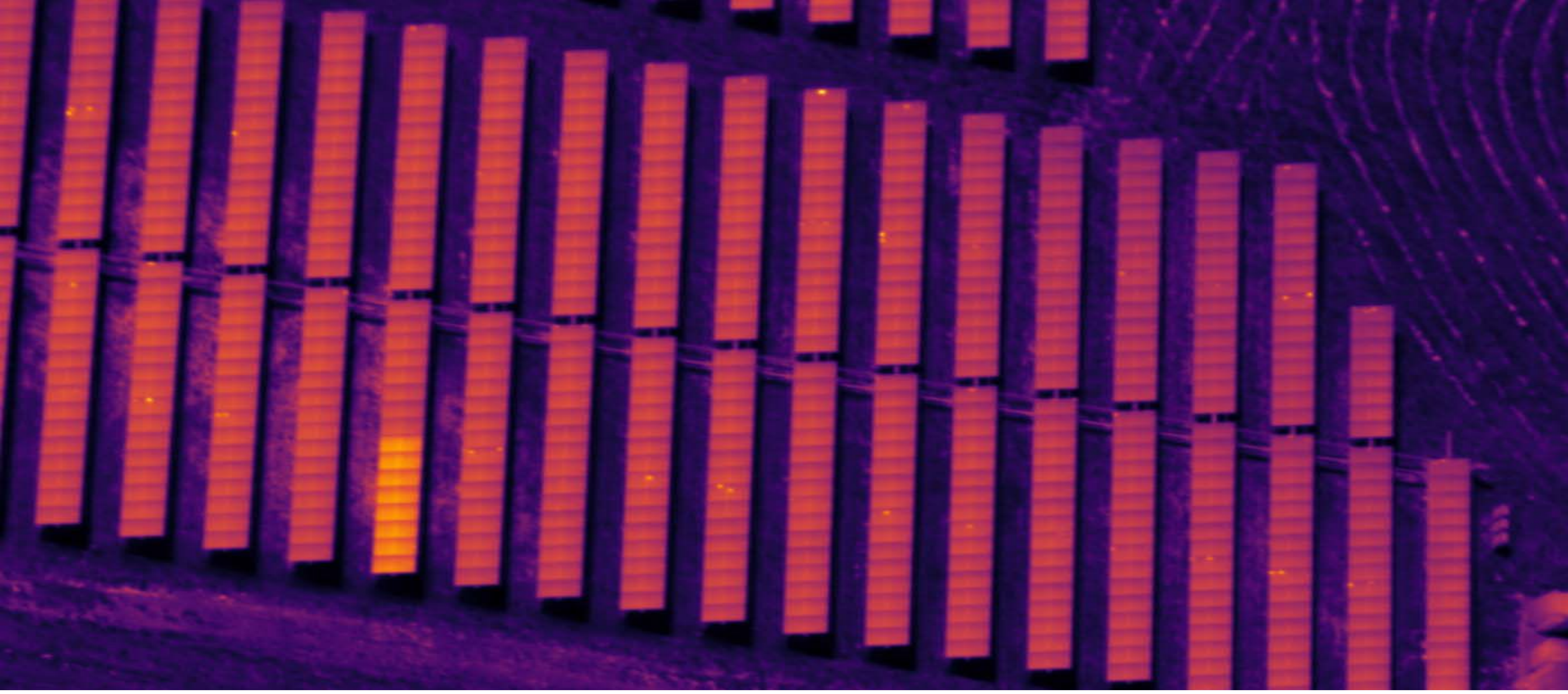
Predictive maintenance informs plant operators how faults will likely develop, enabling staff to make smarter maintenance decisions

Internal defects on PV panels manifest as hotspots. In spite of bypass diode technology, hotspots act as heat sinks and accelerate the degradation of connected components (see Box 1).

Knowing the current and future extent of faults enables plant operators to enact corrective measures at an ideal point in time. Predictive maintenance can bolster risk assessments, minimize emergency repairs and unscheduled downtime, while maintaining optimal plant performance above the threshold where minimum output penalties might come into play (if stipulated by PPAs).

Predictive maintenance improves inventory management and cash flows

Predictive maintenance informs plant staff of the type and number of components that need repair/replacement in the future. This improves inventory management by minimizing the need to stock spare parts, thereby improving cash flows.



Choosing between drone and fixed-wing inspection providers:

- Experience is the primary determinant
- Resolution and flight stability enable drones to capture higher quality images
- Drone services are more compatible with future inspection trends: frequent, targeted and on-demand inspections

Experience is the primary determinant

Inexperience can result in poor flight operations, equipment choice, data collection and analysis. Misconducting any of these processes could lead to low resolution and blurry images, and yield substantially inaccurate fault identifications. Experience not only enables superior fault identification, but it can also translate into better AI functionality.

Resolution and flight stability enable drones to capture higher quality images

Drones typically capture higher resolution thermal images than fixed-wing aircrafts do.

For a fixed-wing aircraft flying 10x higher than a drone with a 640x512 resolution thermal camera, the fixed-wing aircraft would need a thermal camera with 10x greater resolution to capture an image of equal resolution. Our research suggests that such cameras do not exist, even in the military industry.

Drones also have sophisticated flight stabilization systems that benefit image quality. Fixed-wing aircraft have onboard combustion engines that might significantly destabilize their cameras.

Box 2: Fully Autonomous Drone Inspections

Advances in robotics, such as reliable sense-and-avoid capabilities, have made autonomous drone flights beyond visual-line-of-sight (VLOS) possible. Although Part 107 of FAA regulations requires that drone operators be able to intervene autonomous drone flights and keep drones within VLOS, these restrictions are waivable if applicants demonstrate the safety of their operations.[6] Two drone inspection providers confirmed to us that fully autonomous drone inspections of utility scale solar plants have been granted these waivers; one of these providers anticipated that such practices will be standardized in 5-7 years.

Drone services are more compatible with future inspection trends: frequent, targeted and on-demand

Plants conducting routine plant-wide inspections typically do so once a year (Figure 5). More frequent aerial inspections would minimize losses that accrue over time. However, high costs prohibit more frequent aerial inspections.

For frequent aerial inspections to be economically viable, they would need to be cheaper or be provided as part of an unlimited subscription package. Ideally, services would also offer on-demand aerial inspections to inspect problem areas before or as they arise.

Drone firms can meet this ideal with plant-dedicated and autonomous drones. To provide frequent and on-demand inspections, fixed-wing firms need sufficient spatial and temporal density of inspection requests.

Box 3: Quality Control

Not all aerial inspections are performed equally; any number of errors committed by aerial inspection services could severely compromise the reliability of their results. Hence, quality control standards are necessary to assure plant operators that the aerial inspection services they undertake are performed adequately. The International Electrotechnical Commission (IEC) has developed a standard for outdoor thermography with specific criteria for aerial thermography: IEC TS 62446-3:2017.[7]

We briefly tested the industry's knowledge of this standard in our surveys. Of the solar plants we surveyed, none had heard of the standard. When we asked aerial inspection providers for the minimum irradiance level at which they conducted inspections, 1 in 4 firms would perform inspections below the minimum level described in the IEC standard.

According to one of the inspection providers we interviewed, only one US company conforms to the IEC standard in its entirety.

Conditions for effective implementation

Drone inspections are appropriate in the following conditions:

- ➢ 5-20 MW plants now, and larger in the future
- ➢ Plants with storage
- ➢ Plant age is not a condition because young and old plants each derive unique benefits from drone inspections

5-20 MW plants now, and larger in the future

Surveys of solar plants and aerial inspection providers indicated that fixed-wing inspections were cheaper than drone-based inspections for plants larger than 20 MW; however, as labor constitutes a large part of aerial inspection costs, it is anticipated that drone-based inspection services will be more competitively priced for plants >20 MW if and when fully autonomous drone inspection services become common practice.

Plants with storage

Plants without storage have less incentive to increase plant output if they already experience curtailment; off-takers will not purchase excess solar power generated around noon because during that time electricity supply is greater than electricity demand. Although aerial inspections by themselves are typically cheaper than manual inspections, aerial inspections are perceived as an additional cost because plant operators may opt for a transitionary period whereby both manual and aerial inspections of the entire site are employed.

Considering the pervasive trend towards solar + storage, curtailment will be less of a constraint on the benefits of aerial inspections in the future.

"The greatest motivator to maximize plant efficiency is being able to store it"
- SunPower O&M Manager

Plant age is not a condition because young and old plants each derive unique benefits from drone inspections

Older plants tend to have more defects as faults inevitably develop in older equipment; however, new equipment is also difficult to manage as it is more prone to random defects (see page 26 for contrasting survey responses that favor drone inspections of young and old plants). Frequent and on-demand inspections of young and old plants would prevent isolated faults developing into wider-spread performance compromising issues.

Solar's exponential growth necessitates aerial inspections

Market trajectory

- The growth of utility scale solar installations has exceeded all predictions (Figure 1).[2]
- Solar power continues to displace fossil fuels. From 2010 to 2017, solar increased its share of total U.S. energy generation from 0.1% to 2%,[1] and it is likely that by 2050, 21% of electricity in the U.S. will come from solar power, representing as much as 316 GW of energy.[8]
- Although previously driven by investment tax credits and falling installation costs (Figures 2 & 3),[1] the solar industry is evolving.
- Nameplate capacities are growing exponentially. The largest installations over the years are shown below.[9] Currently, the largest project in the pipeline is a 200 GW plant in Saudi Arabia (PPA signed), which is more than 100x larger than the Tennger solar plant.[10]

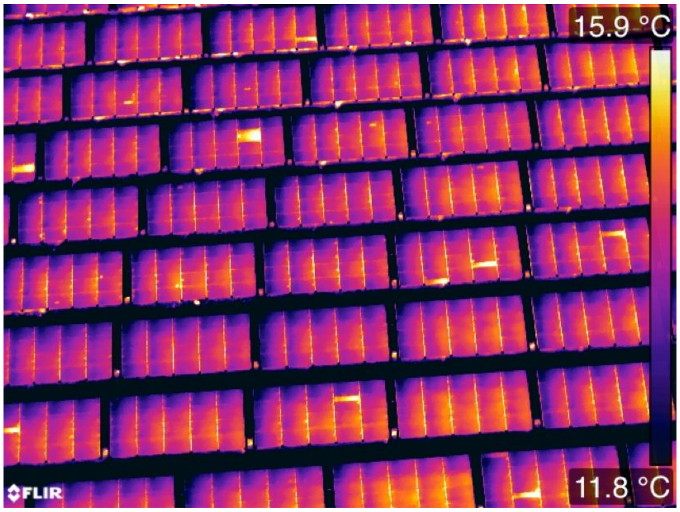
Solarpark Mühlhausen, 2005, 6.3 MW

Agua Caliente Solar Project, 2012, 290 MW

Tengger Solar Plant, 2016, 1547 MW

Necessarily, industry will shift towards more efficient and cost-effective O&M

- Even a 1% decrease in output can, for a 12 MWdc plant, translate into annual revenue losses in excess of $209,000; such was the case with the plant shown below.



<u>Losses due to defects in this shot alone</u>
– 2100W deficit at average annual irradiance level
– 2.2 MWh lost per year
– $330 lost per year

(this shot shows 40 tables; 180kW;
1% of the plant, not including inverters)

- Manual inspections = high labour costs and inefficiencies.

- Monitoring systems = smaller but incrementally significant defects go unnoticed.

- These issues can be readily addressed by aerial inspections, by drone or fixed-wing aircraft.

Aerial inspections reduce O&M costs

- Lower inspection costs (Figure 6).
- Shorter inspection times (Figure 5).
- Improve preventative maintenance by reducing losses that accrue over time.
- Enable predictive maintenance:
  → Prevent problems from developing;
  → Reduce losses due to unscheduled downtime;
  → Streamline inventory management.

Opportunities for additional innovation in aerial inspections are enormous

- Aerial inspections already outperform other inspection methods.
- With rapid developments in drone, battery, AI, and sensor technologies, the advantages will only increase.
- Digitalization of inspections and smart image-processing will revolutionize utility scale O&M, maximizing output and efficiencies.

The transition to more sophisticated inspection and maintenance practices is integral to maximizing renewable energy output.

Sources

Articles

[1] *Solar Industry Research Data*. Solar Energy Industry Association, www.seia.org/solar-industry-research-data. Accessed 20 Aug. 2018.

[2] O'Rourke, Steve. "Capitas Energy." 14 Mar. 2018, *Solar Asset Management North America 18.* San Francisco.

[3] Horwitz, Yuri. "Why Solar Is on a Path to Dominance." *Green Tech Media*, 15 Feb. 2018, www.greentechmedia.com/articles/read/solar-is-going-to-win-bigly#gs.f6CAf2s.

[4] Fu, Ran, et al.*U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017*. National Renewable Energy Laboratory, 2017. www.nrel.gov/docs/fy17osti/68925.pdf.

[5] Yole Développement. "Sensors for Drones and Robots: Market Opportunities and Technology Revolution." 2016, www.yole.fr/2014-galery-MEMS.aspx#.

[6] U.S. Department of Transportation. *Operation and Certification of Small Unmanned Aircraft Systems*. Federal Aviation Authority, 2016. www.faa.gov/uas/media/RIN_2120-AJ60_Clean_Signed.pdf. Accessed 20 Aug. 2018.

[7] International Electrotechnical Commission. "IEC TS 62446-3:2017." *IEC Webstore*, webstore.iec.ch/publication/28628. Accessed 20 Aug. 2018.

[8] U.S. Energy Information Administration. *Annual Energy Outlook 2017: With Projections to 2050*. 2017. www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf.

[9] Wikipedia. "List of Photovoltaic Power Stations." *Wikipedia*, Wikimedia Foundation, Inc, 15 Aug. 2018, en.wikipedia.org/wiki/List_of_photovoltaic_power_stations. Accessed 20 Aug. 2018.Rathi,

[10] Akshat, and David Yanofsky. "What Saudi Arabia’s 200 GW Solar Power Plant would Look Like — If Placed in your Neighborhood." *Quartz*, 1 Apr. 2018, qz.com/1240862/what-saudi-arabias-200-gw-solar-power-plant-would-look-like-from-space/.

Interviews

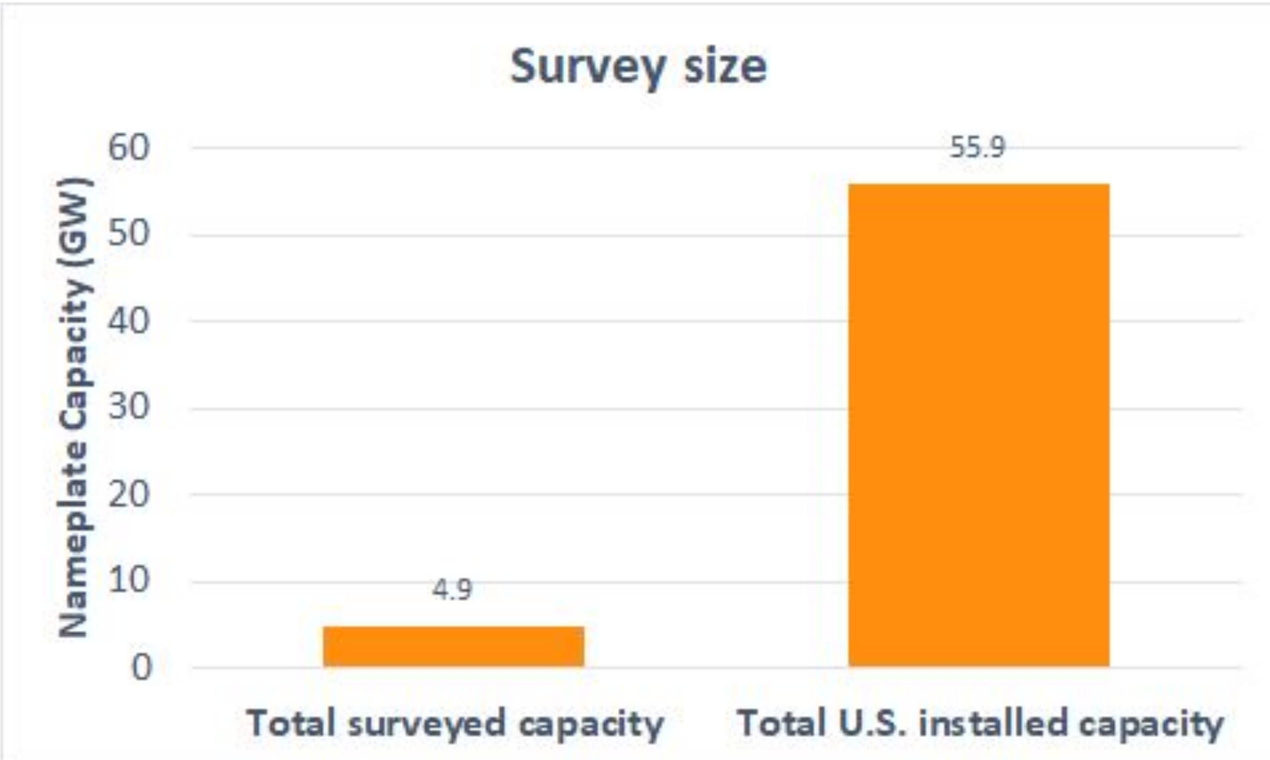
Steven Katz, CMO & USA Manager, Cleandrone
Ricard Pardell, CEO & Founder, Cleandrone
Fabien Vagnot, CEO, Gimball-Prod
Scott Innes, CFO, Heliolytics
Mark Culpepper, CEO & Founder, Precision XYZ Aerial Services
Kingsley Chen, UAV Fleet Coordinator, SunPower Corporation
Kyle Cobb, Business Developer and Sr. Product Manager, SunPower Corporation
Nick McKee, Manager of Asset Operations, AES Distributed Energy
Steve O’Rourke, Managing Partner, Capitas Energy
Upshur Quinby, Portfolio Manager, Concord New Energy
Timo Moeller, Commercial Director of Energy Services, First Solar
Tom Buttgenbach, President & Co-Founder, 8minutenergy Renewables
Leigh Zanone, Director of PV Plant Performance, 8minutenergy Renewables

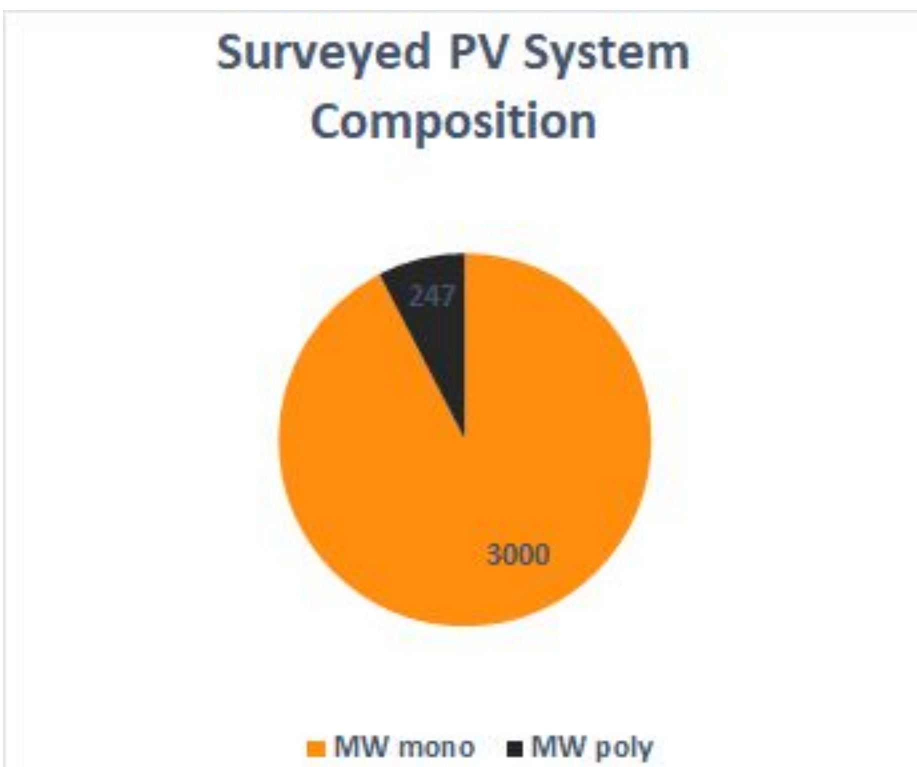
Surveys – Utility Scale Solar Plants
8minutenergy Renewables
SolarReserve
SunPower Corporation
sPower
Clenera

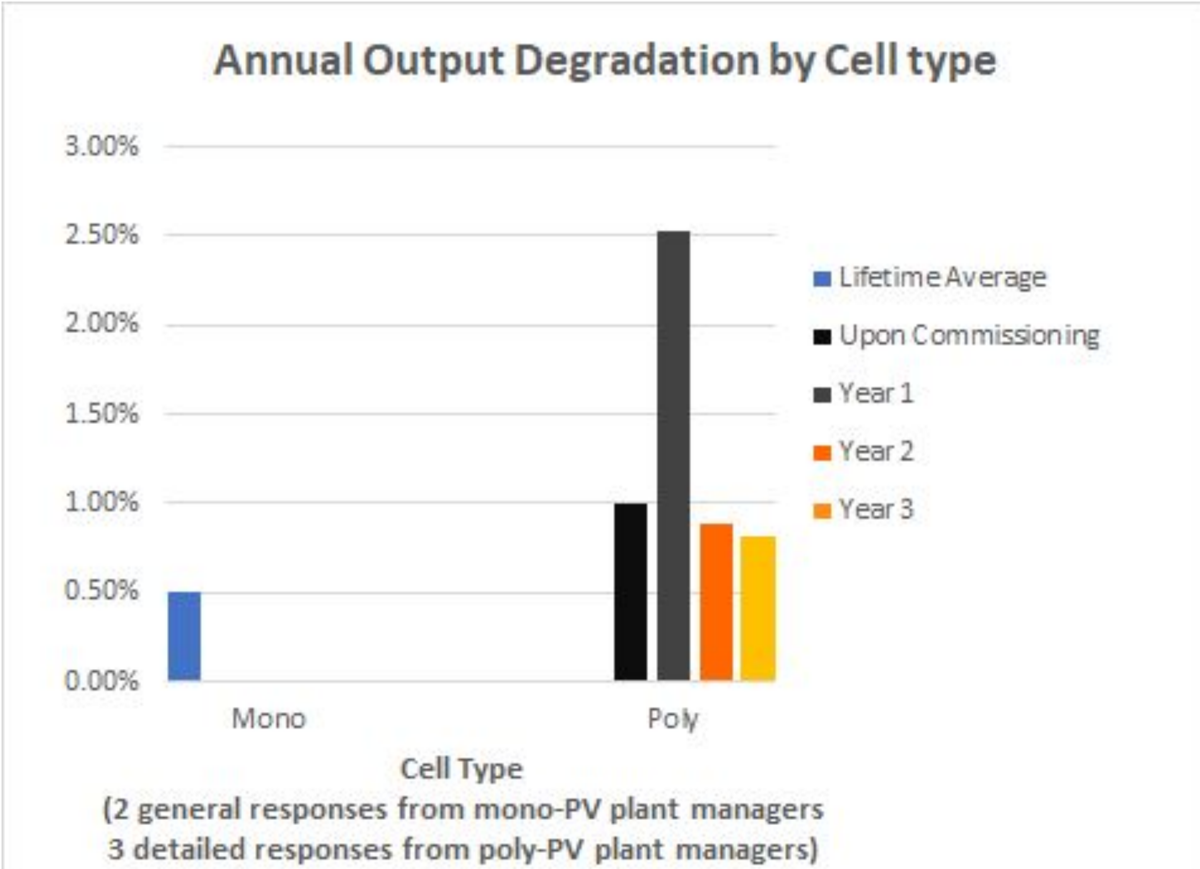
Surveys – Aerial Inspection Services
AeroSpec Technologies
Cleandrone
Eneretis
Heliolytics
HUVR
Precision XYZ Aerial Services

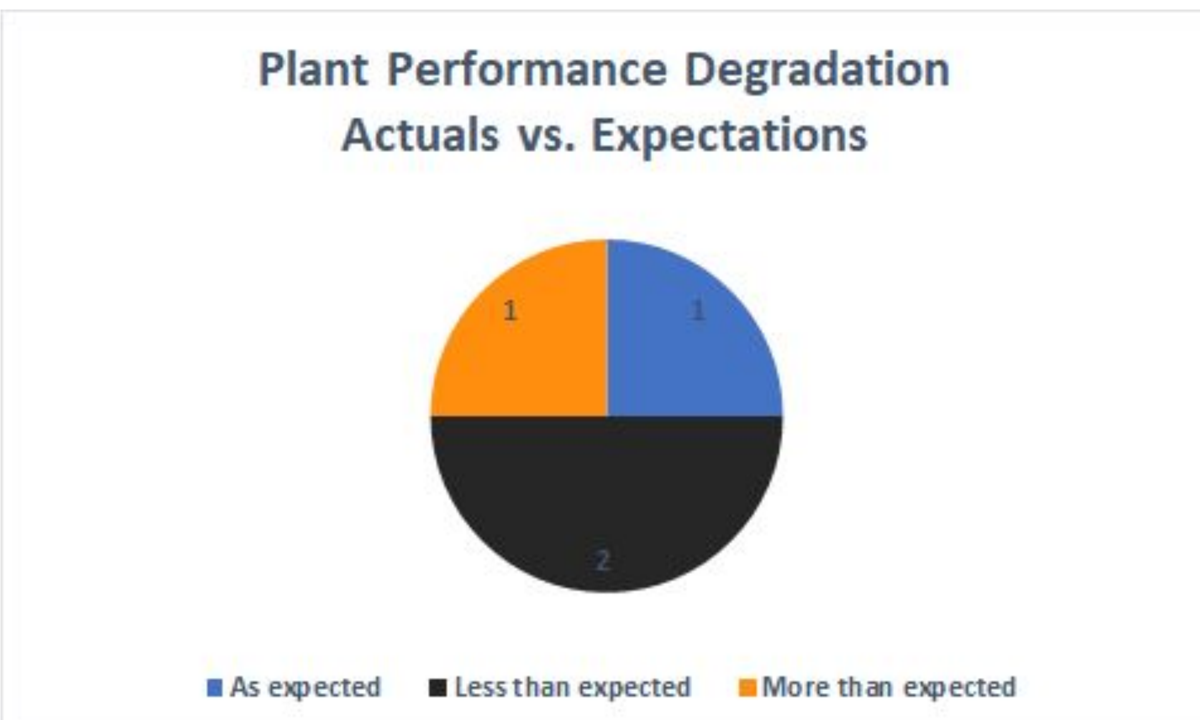
Other
Solar Asset Management Conference North America 2018, organized by Solar Plaza, with special thanks to Kostis Tzanakakis and Marcel Langone
UCLA Institute for the Environment and Sustainability (IoES), Peter Kareiva (Director) and Board of Advisors

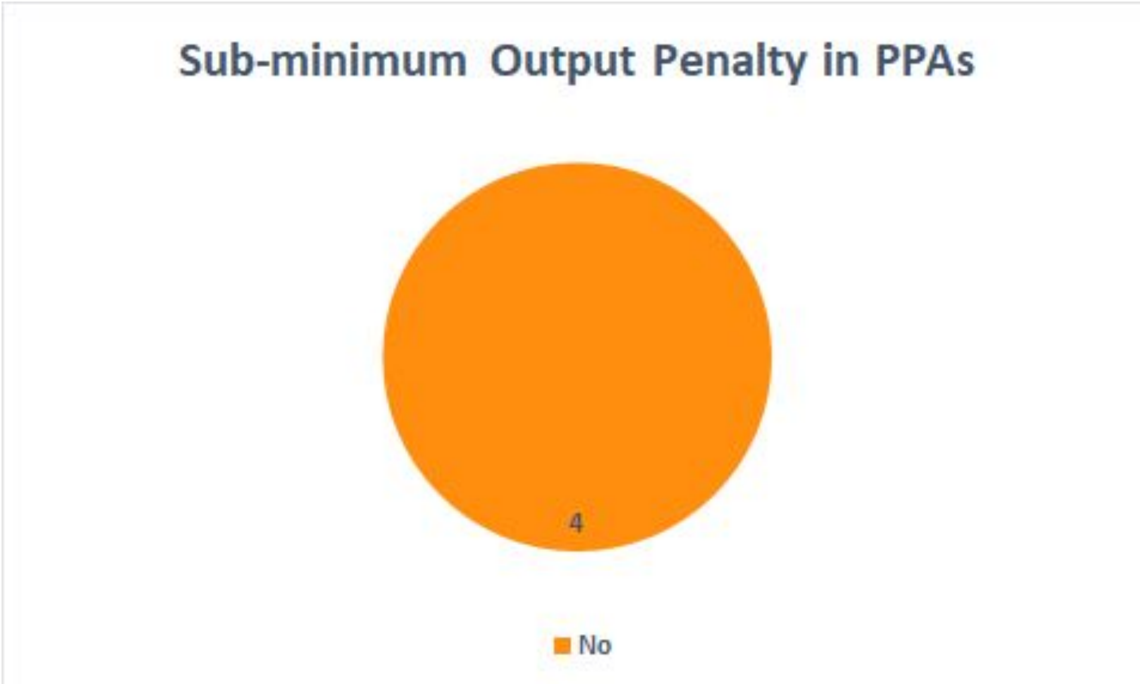
Appendix 1: Original Data – Solar Plants



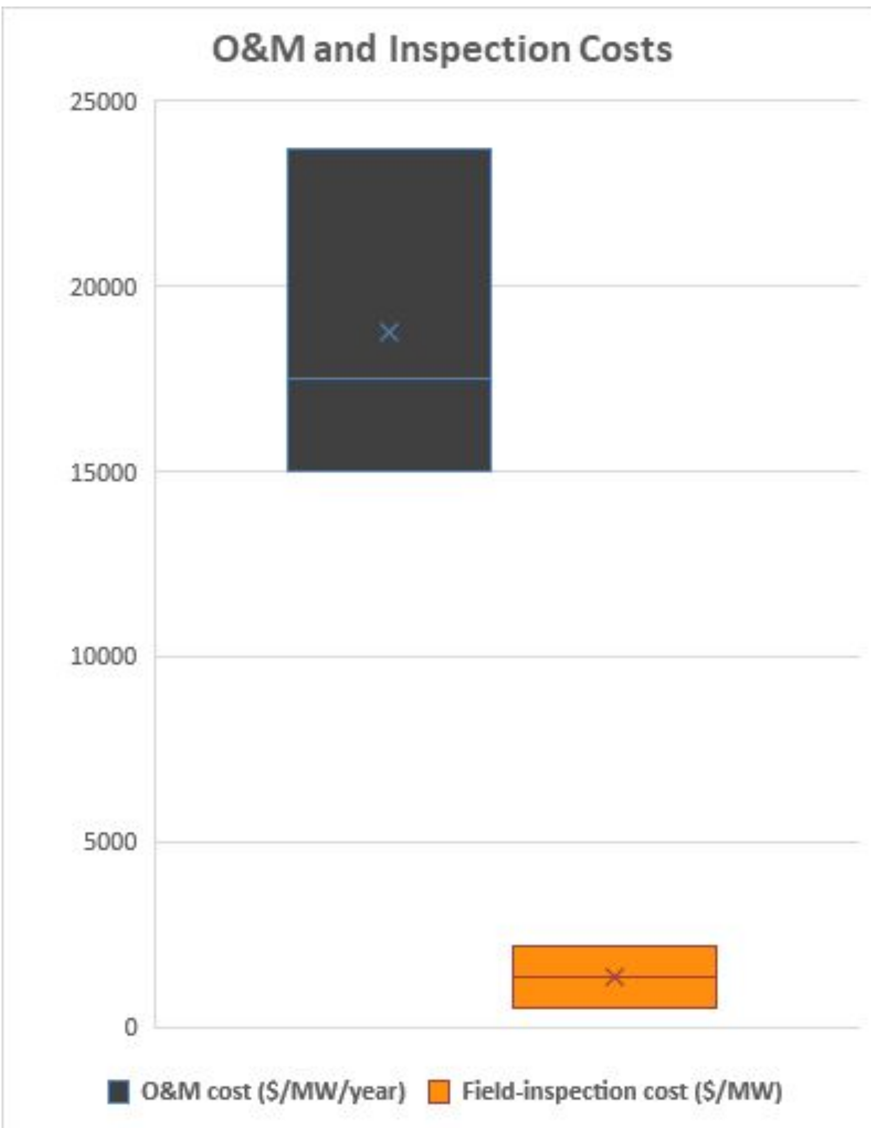



Annual Output Degradation by Cell type
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
Mono
Poly
Lifetime Average
Upon Commissioning
Year 1
Year 2
Year 3
Cell Type
(2 general responses from mono-PV plant managers
3 detailed responses from poly-PV plant managers)


Plant Performance Degradation
Actuals vs. Expectations
1
1
2
As expected
Less than expected
More than expected



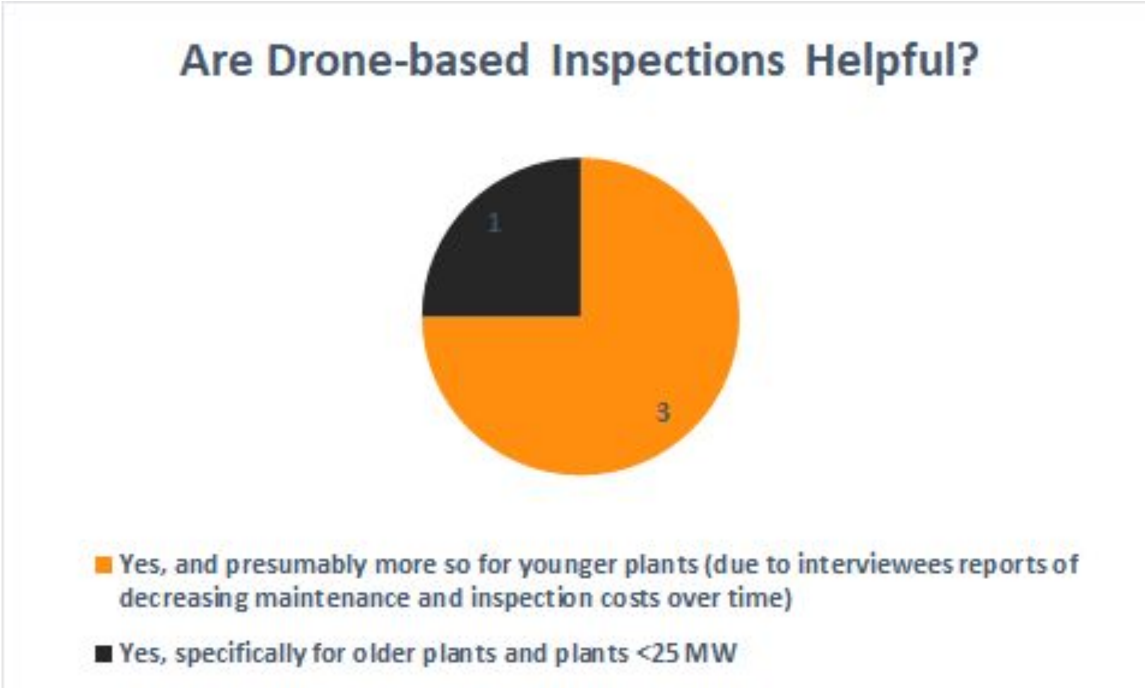
Sub-minimum Output Penalty in PPAs
4
No



O&M and Inspection Costs
25000
20000
15000
10000
5000
0
O&M cost ($/MW/year)
Field-inspection cost ($/MW)

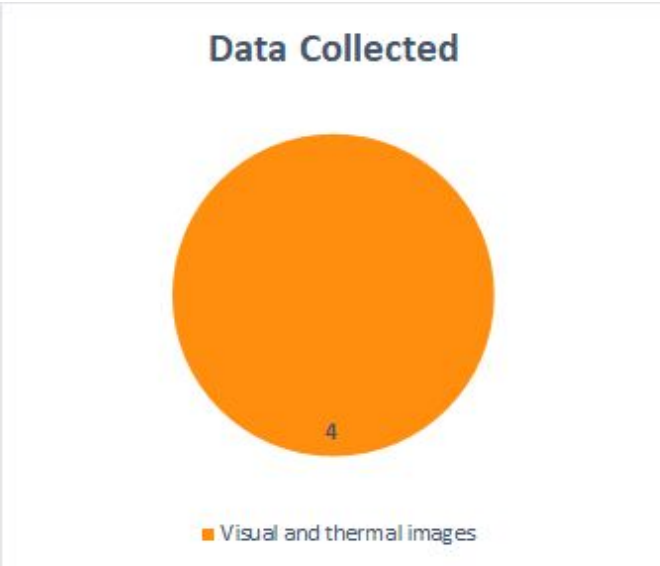
n=3

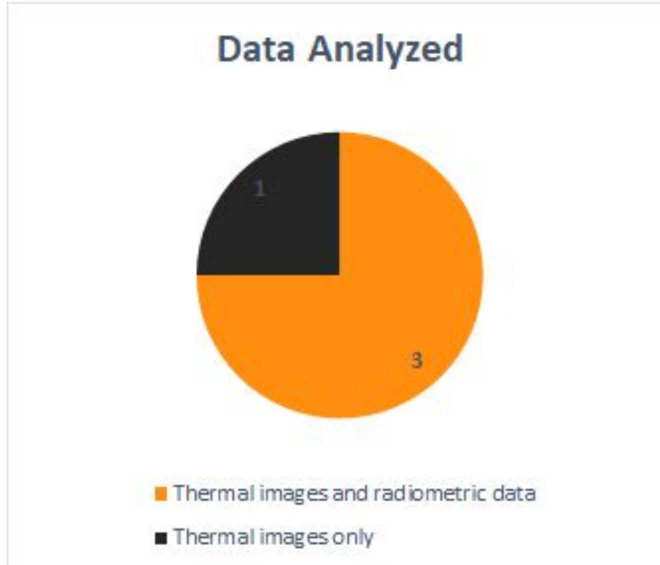
n=2

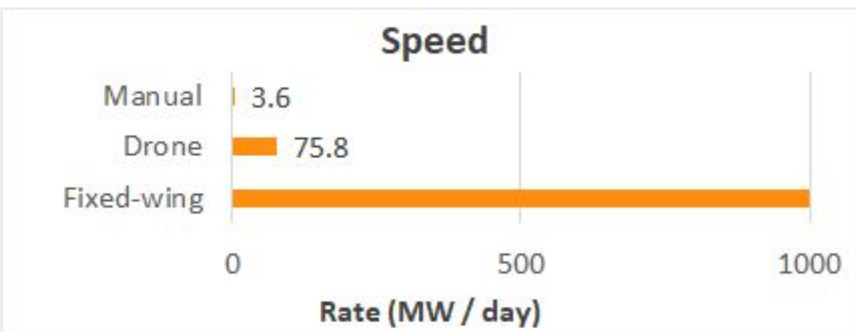


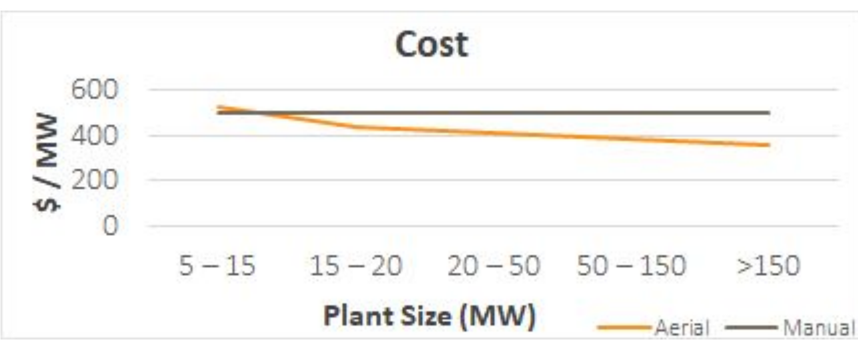
Are Drone-based Inspections Helpful?
1
3
Yes, and presumably more so for younger plants (due to interviewees reports of decreasing maintenance and inspection costs over time)
Yes, specifically for older plants and plants <25 MW

Appendix 2: Original Data – Aerial Inspection Providers



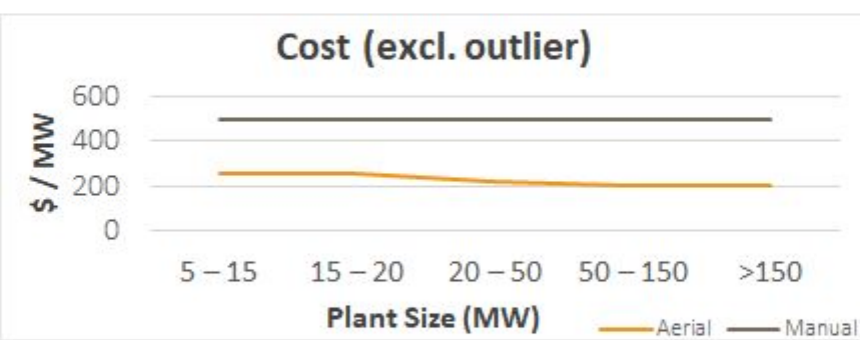




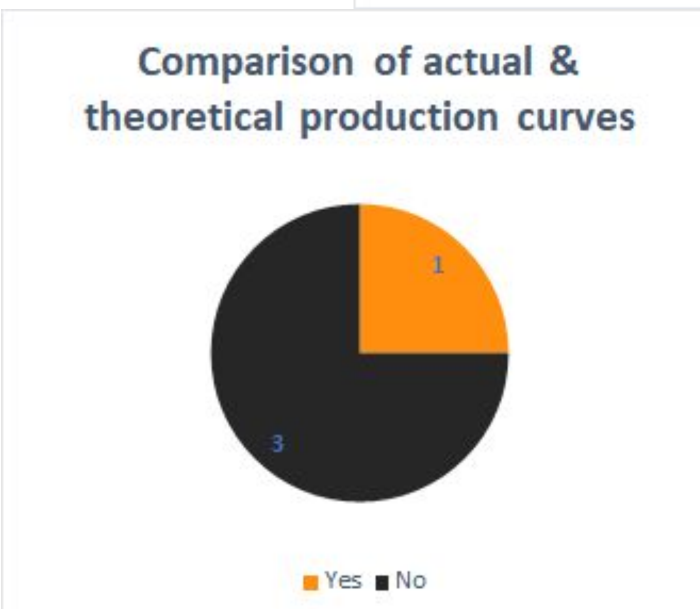


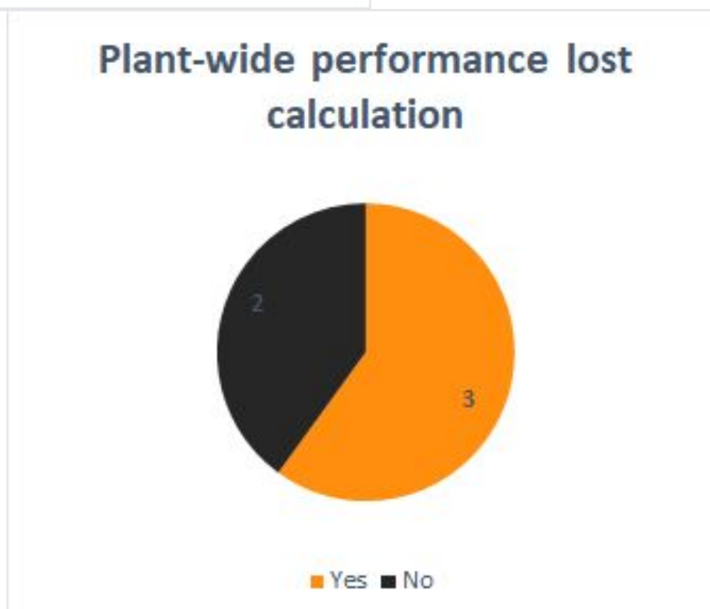
Aerial inspection providers that responded to cost and speed questions, n=4

N.B. average aerial inspection costs compared to lowest manual inspection cost

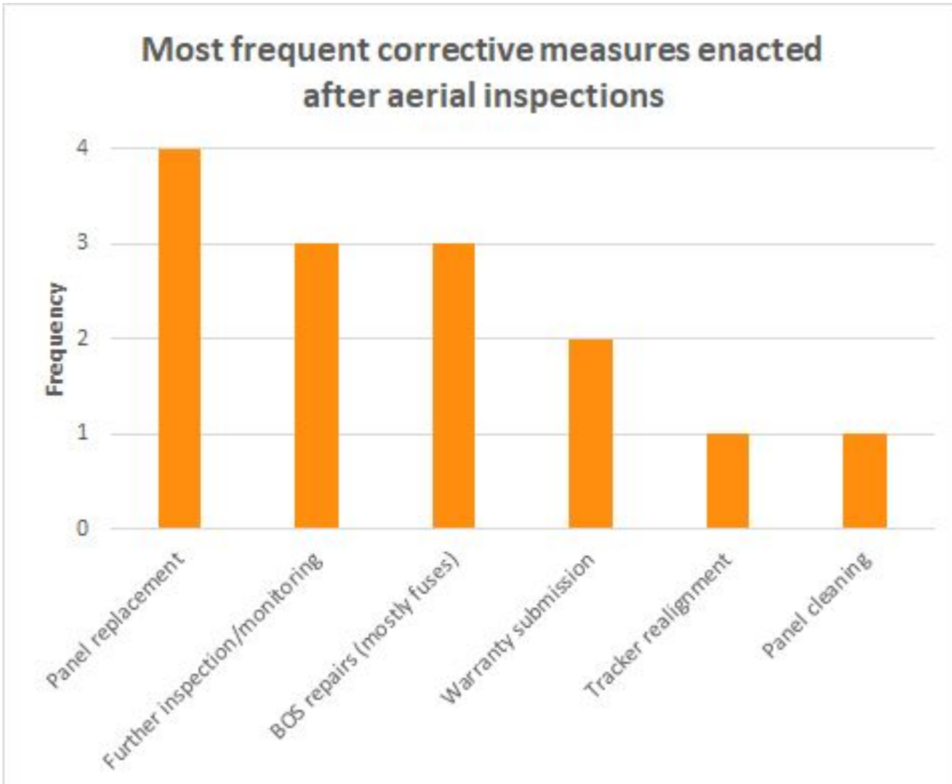


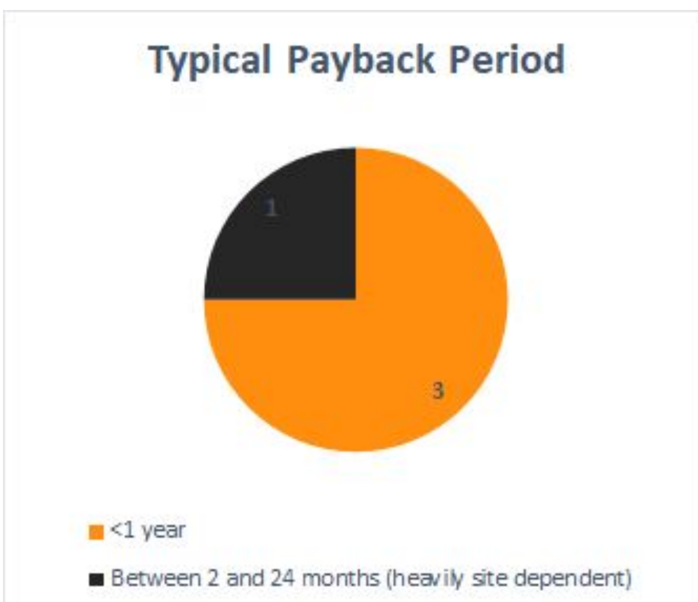
Post-inspection report contents:





Following post-inspection report:





Testing aerial inspection quality against IEC outdoor thermography standard (which says minimum irradiance for inspections should be 600 W/m^2):