Leveraging Infrared Drone Imaging for the District Heating Sector

Adam R. Jensen
Janne Dragsted

Technical report

DTU Civil Engineering

2019

DTU Byg - report no. 427 (ENG)
December 2019

DTU Civil Engineering

Department of Civil Engineering

Preface

This report presents an investigations on how drone thermal imaging can be leveraged in the district heating sector. The focus of the project has been on solar heating systems, specifically investigating whether it is possible to detect uneven flow distribution in solar collector fields and if drone thermal imaging can be used to detect thermal bridges in pit thermal energy storages. The project was carried out from 2017 to 2019.

The authors gratefully acknowledge Bjarne Saxhofs Fond for financially supporting this project.

Contents

Introduction

Within the last decade, drones have evolved from military aircrafts and hobby racing drones to enter the consumer and commercial market in great numbers. Some of the main reasons for this are new advancements in drone technology, including better cameras, ease of piloting, and lower costs. With the introduction of drones into the consumer and commercial market, a number of new opportunities and applications are ready to be explored. Drones are especially useful when coupled with thermal cameras that can detect beyond the capability of the human eye in the infrared spectrum. Already existing commercial applications using drone thermal imaging include building inspections, fault detection of power lines, agriculture surveying, and search & rescue.

It is believed that drone thermal imaging has a large untapped potential concerning applications within the district heating sector, providing services which otherwise have been too time consuming, costly, or simply impossible. This technology has already been applied by a number of companies who use drone services to locate leakages in district heating networks. Another existing application within the utility sector is inspecting and locating faults in photo-voltaic plants [Scheuerplug 2014, Vadhaykar 2017].

The aim of this project has been to investigate new areas within the district heating sector, where drone thermal imaging can be leveraged. Two key areas have been identified that have large potential in terms of increased performance of district heating plants and costs savings. The first area concerns large-scale solar collector fields that often span many hectares, hence why manual inspection is often not an option due to the prohibitive time requirement. Specifically this project will investigate whether it is possible to determine the occurrence of uneven flow distribution in collector rows. The second application that this project will investigate is whether it is possible to detect leakages and thermal bridges in pit thermal energy storages, which are large hot water reservoirs with floating insulated lids.

The project takes a practical approach, first surveying the market for thermal cameras and drones, providing the reader with an overview and lists out the pros and cons of the different possibilities. Based on the findings, a suitable thermal camera and drone solution will be purchased, in order to test and validate the aforementioned applications in the real-world.

To investigate the possible applications of thermal drone imaging in the district heating sector, this report proceeds as follows. First, a market overview and discussion of suitable of-the-shelf thermal imaging cameras and drones is given. Then, a description of drone and thermal camera purchased and used in the project is presented. Next, results from applying thermal drone imaging to investigate solar district heating plants and pit thermal energy storages are presented and discussed. Last, the project findings are concluded and the dissemination activities of the project are described.

N.B.: It is important to note that this report only briefly points out certain regulations concerning drone operations. Users should undertake a drone course and certification (3 days, approx. 4800 DKK) before carrying out any serious drone operations.

Thermal Imaging

Thermal cameras, also known as infrared or thermographic cameras, create images based on infrared (IR) radiation emitted by objects. Whereas regular cameras detect visible light, which is in the range of 400 to 700 nm, infrared cameras detect wavelengths in the infrared spectrum, typically from 7.5 to 13.5 µm. Thermal cameras, therefore, do not directly detect temperature, but rather rely on the principle that every object emits radiation as a function of temperature.

Thermal cameras have the capability of converting the IR part of the spectrum into visualizations that humans otherwise cannot detect [OPGAL 2018]. However, the process of converting the detected infrared radiation to temperature is not flawless. For example, the infrared radiation emitted by an object depends on the objects emissivity, which in most cases must be estimated. Emissivity is a radiative property of a surface and is quantified as the ratio of emitted energy from a surface to that of a perfect blackbody surface. Emissivity ranges from 0 to 1, corresponding to a perfect mirror and a perfect blackbody, respectively. A surface's emissivity depends primarily on the material and on the surface finish, e.g. polished, painted, etc. The emissivity of some common surfaces is given in Table 2, where the effect of surface finish can be seen for aluminum, which has an emissivity of 0.04 when polished and 0.82 when anodized.

Table 2: Emissivity of common surfaces at 300 K [DeWitt, 2011].

Material	**Emissivity**
Aluminum (anodized)	0.82
Aluminum (polished)	0.04
Paints (black)	0.98
Paints (white)	0.90
Sand	0.90
Soil	0.93-0.96
Vegetation	0.92-0.96
Water	0.96

A surface with a low emissivity acts in part as a mirror, reflecting some amount of infrared radiation. For slanted or horizontal surfaces, e.g. solar collectors, the cold IR emitted by the sky is partly reflected from the surface. Warm objects, e.g. chimneys, in the field of view can also influence the infrared radiation reflected by an object, hence why it is important to consider the surface type and the surroundings when making thermal images. Another important aspect to consider is water, as surfaces that are moist or wet have a different emissivity than when dry. As seen in Table 2, the emissivity of water is 0.96, which means that the wet areas of an object typically are erroneously detected as having a higher temperature. Surface water can also impact the temperature of an object due to evaporation of the water, reducing the temperature of the object.

It should now be evident that there are many factors to consider when taking thermal images. The most important factor to consider is the emissivity of the object in question. In order to get the most accurate temperature reading possible, it is necessary to use the correct emissivity, which can be adjusted in the settings of most thermal cameras. For example, if one is focusing on black painted objects, then the emissivity should be set to 0.98. For surfaces with an emissivity less than 0.5, reflections of infrared radiation are typically so high that measurements are unreliable and inaccurate. To overcome this, it is possible to increase the object's emissivity. This can be done, for example, by painting the object or applying a piece of tape of known emissivity to the object that can be later removed.

Thermal Cameras for Drones

When deciding on which thermal camera to acquire, the most important aspects to consider are resolution, price, and how the camera will be integrated with the drone. It is important to keep in mind that the resolution of thermal cameras is generally much lower than that of regular cameras. An overview of the most common thermal cameras used for drone applications is listed in Table 3, with key details, including resolution and price.

There are essentially three options in regards to thermal camera - drone integration. The first option is utilizing drones that have a built-in IR camera. The second option is similar to the first, where the camera is native to the drone, but detachable. The third option is using a stand-alone IR camera with a suitable gimbal. Each of the three solutions has its own advantages and disadvantages, which will be discussed in the following sections.

Drones with built-in IR cameras have the advantage of being very compact, lightweight, and are by far the cheapest solution for thermal drone photography. The main disadvantage of this solution is the low resolution of these thermal cameras. The two most notable drones in this category are Parrot's Anafi Thermal and DJI's Mavic 2 Enterprise Dual. Both of these drones uses FLIR's Lepton sensor, which has a resolution of 160x120 pixels. The low resolution is sufficient for operations where the distance to the inspection surface is short, such as for roof and building inspections. For applications within the district heating sector, where large areas often have to be surveyed (such as district heating networks, solar collector fields, etc.), the resolution is insufficient. Therefore, due to the low thermal resolution, the currently available drones with built-in IR cameras are deemed unsuitable for applications within the district heating sector.

Drone manufactures have also recently entered the market of thermal cameras, offering detachable cameras that seamlessly integrate with the manufactures' own platform. Compared to drones with built-in IR cameras, this solution offers greater thermal resolution, but at a higher cost. Currently only DJI and Yuneec offer such solutions. DJI has two thermal cameras, the Zenmuse XT and the Zenmuse XT2. Both cameras are available with two different resolutions: a medium resolution version with 360x256 pixels and a high resolution version with 640x512 pixels. Yuneec also offers two cameras, their E10T camera and the CGOET camera. The CGOET camera is a low resolution camera with only 160x120 pixels, and therefore not suitable for the reasons discussed in the previous section. The E10T camera, however, uses FLIR's bosom sensor and is available in both medium and high resolution, with 320x256 pixels and 640x512 pixels, respectively. Another feature of both DJI's Zenmuse cameras and Yuneec's E10T camera, is that they are available with different lenses, e.g. focal lengths of 9 mm, 11mm, or 13 mm.

A drawback to the detachable cameras mentioned above, is that they can only be used with the manufactures' own drones, and even then often only a few select drone models. The DJI Zenmuse XT camera can, for example, be used with the Inspire 1 and the Matrice 100, 200 and 600 series. The newer DJI Zenmuse XT2 can only be used with the Matrice 200 series and the Matrice 600 pro. Similarly, Yuneec's E10T camera can only be used with the Yuneec's H520 Hexacopter.

The third option is to use a stand-alone IR camera. This is the most flexible of the three solutions, allowing virtually any smaller IR camera to be used. The drawback is that the integration is more complex and often requires a custom solution. A suitable gimbal must be obtained and a method for interfacing with the drone needs to be created. Both of these challenges are not present when using either of the previous methods, however, this third solution does afford a much larger selection of cameras that can be used, often with more advanced settings. This option is most often used by researchers at universities and specialized consulting companies who require more advanced custom solutions. Some of the most frequently used IR cameras for this method include FLIR's Duo and Tau models. See Table 3 for a comparison of selected IR cameras.

After having discussed the three integration options, IR cameras can also be differentiated by their update frequency, which is often expressed in how many frames per second (fps) the camera is able to capture. The most common frequencies are 9 Hz and 30 Hz. A high frame rate is most important when shooting video, as otherwise the video will not appear smooth. However, most thermal drone applications do not involve video, but rather a series of photos which can be stitched together or processed individually. Therefore, a frame rate higher than 9 Hz is often not necessary and not worth the extra cost. To illustrate the cost difference for the same camera with two different frame rates, consider the Zenmuse XT2, which costs around 68 000 DKK for the 9 Hz version and 91 000 DKK for the 30 Hz version.

Another feature to consider when deciding on a thermal camera is whether or not it is desirable to have a dual camera, which captures a regular image concurrently with the thermal image. This can be a good option when the thermal images are taken during daylight, as it is easy to compare the features of the thermal image with that of a regular image. For example, in the case of inspection of buildings or PV modules, an abnormality in the thermal view might just be caused by debris, which can be detected in the RGB image, and should not be further investigated. A number of the cameras discussed previously have a dual sensor, including DJI's Zenmuse XT2, both cameras from Yuneec, as well as FLIR's Duo camera.

Table 3. Key information concerning the most commonly used thermal cameras for drone application.

	Model	Radiometric	Price DKK*	Thermal resolution	RGB resolution pixels
FLIR	Duo	No	8 000	160x120	1920x1080
	Duo R	Yes	10 000	160x120	1920x1080
	Duo Pro R	Yes	33 000 55 000	336×256 640×512	4000x3000
	Vue	No	10 000	336 x 256	n/a
	Vue Pro	No	14 000		n/a
	Vue Pro R	Yes	23 000 n/a	336×256 640×512	n/a
DJI	Zenmuse XT	No No Yes Yes	n/a	336×256 640×512 336×256 640×512	n/a
	Zenmuse XT2	Yes	40 000	336×256	3840×2160
	Zenmuse XT2	Yes	68 000	640×512	3840×2160
Yuneec	E10T E10Tv	No No	37 000 ~60 000	320 x 256 640 x 512	1945x1097
	CGOET	n/a	15 000	160x120	1920x1080
Workswell	Wiris 640	Yes	40 000	640x512	1600x1200

*Prices are excluding VAT and estimated from various online retailers.

Drones for Thermal Imaging

Drones span virtually any price and weight class, from sub-250 gram micro drones that can be acquired for less than $100, to multi-ton armed military aircrafts. In this project, the focus is on off-the-shelf, commercially available drones, as these are relatively low cost, easily acquired, and can be operated without expert knowledge. Drones that satisfy these criteria can, with moderate effort, be adopted by district heating companies themselves or by consulting companies offering drone inspection services.

According to regulations set out by the Danish authorities, drones are classified into three different categories: 1A for drones weighing less than 1.5 kg, 1B for drones between 1.5 kg and 7 kg, and category 2 for drones between 7 kg and 25 kg. The respective weights given for each category refer to the start weight of the drone, which includes the drone itself and all ancillary equipment, such as cameras or other payloads. The main difference between the categories concerns their requirements for certification. The certification for 1A consists only of a written examination, whereas certification for category 1B and 2, additionally require a practical flight exam with a drone in the respective category. Examples of drones in each of the categories are given in Table 1.

Table 1: Examples of drones based on weight categories. Drones with built-in cameras are in green, whereas cameras with attachable cameras are in red.

Category 1A (0-1.5 kg)	**Category 1B (1.5-7 kg)**	**Category 2 (7-25 kg)**
DJI Phantom	DJI Inspire 1/2	DJI Matrice 600 Pro
DJI Mavic Pro	DJI Matrice 100	DJI S1000
DJI Mavic Enterprise Dual	DJI Matrice 200/210	DJI S900
Parrot BEBOP 2	Yuneec Typhoon H	
Parrot Anafi Thermal	Yuneec H52	
DJI Spark		

When choosing a specific drone for thermal imaging, the most important consideration is what type of thermal imaging solution is desired, as described in the previous section, and which thermal camera will be used. For the solution with built-in IR cameras, the choice is limited to the models in green in Table 1. Likewise, when choosing the solution using a native detachable IR camera, the drone models are limited to those in red in Table 1. When using a standalone IR camera with a gimbal, the options for drones are much greater, and the most important considerations are carrying capacity and drone-camera-interfacing options.

Experimental Setup

An important aspect of this project was that the methods and procedures used could easily be adopted by district heating companies if found successful. Since the applications investigated in this project involved covering large areas, a high-resolution thermal camera was chosen. For these reasons, DJI's Zenmuse XT2 640x512 resolution camera with a 13 mm lens was purchased, as it is a high resolution camera that can be easily integrated with the DJI Matrice 200 drone platform. A DJI Matrice 200 was also purchased, which is the cheapest of drone that is able to integrate with the Zenmuse XT2 camera. Since the project was application focused, a commercial program for flight path programming and image stitching was used, specifically DroneDeploy. The entire solution was extremely easy to setup and use, and offered seamless integration between the camera, drone, and image processing program.

Results and Conclusions

Two key unexplored areas that could greatly benefit from the use of thermal drone imaging have been identified within the district heating sector. The first area is inspection of solar collector fields in order to determine if there is uneven flow distribution between rows. The second topic is detection of leaks and thermal bridges in pit thermal energy storage lids. Both of these two areas are explored in the following section, showcasing images from drone operations carried out within this project with the purpose of investigating and determining the feasibility of the two applications.

Solar collector fields

Three solar collector fields have been investigated during the project period, including the world's largest in Silkeborg and a plant near Høje Taastrup. The primary objective was to investigate whether it was possible to detect uneven flow distribution between the various collector rows in large-scale solar collector fields. Therefore, only the last collector in each row was inspected, as all end row collectors should have the same temperature in the case of even flow distribution. Whether it is possible to actually determine a temperature difference was unknown at the start of the project. Due to the prohibitive time requirement of manual inspection with thermal cameras, such investigations had never been carried out. This is why drone inspections were chosen, as these have the potential to cover large areas during a short time frame.

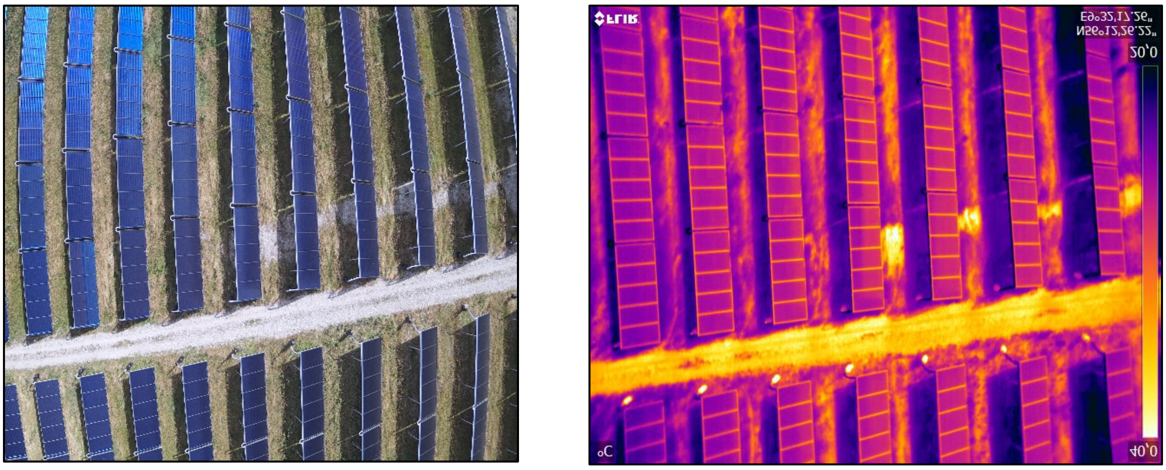

Figure 2. RGB image compared to a thermal image of end row collectors in Silkeborg. Altitude approx. 30 m.

Many operations were carried out, flying over the end row collectors from multiple heights, speeds, etc., to test if it was possible to determine any significant temperature difference between end row collectors. Eventually, however, it was determined, due to a number of reasons, that the temperature differences due to potential uneven flow distribution could not be detected.

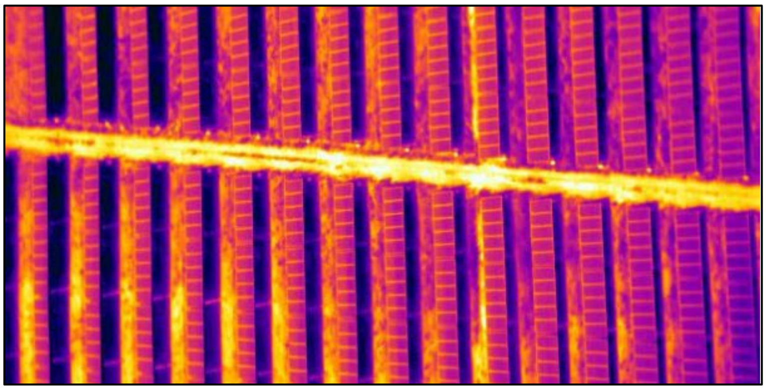

Figure 3. Thermal image of Silkeborg solar collector field part AB, from an altitude of approx. 100 m.

The images were primarily gathered during periods of high sunlight, which is desired when inspecting solar thermal collectors or PV panels, as the greatest temperature differences between collectors occur during these conditions. The drawback to operating in cloudless conditions is that higher reflections from sunlight and from the cold clear sky also influence the measurements, especially for surfaces with low emissivities. It was noticed that the reflection was dependent on the angle to the camera, as the same collector would have a noticeable different temperature dependent on if it was in the center of the field of view or near the edges. This phenomenon is visible in Figure 3, where it seems that the collectors in the right part of the image are colder than those at the left part, however, when the camera was moved the temperature field changed due to reflections.

Perhaps the most influential reason why it was not possible to detect any temperature difference, is that only the temperature of the surface glass can be detected and not the collector receiver itself, which is the part that is heated up by the sun. The glass surface is cooled down from exposure to the ambient air, which means that a significant temperature between two solar collector receivers might not show up as significant when looking at the front glass.

The outlet pipes from each collector could potentially be better suited for comparing the outlet temperatures, however, these pipes are enclosed in a reflective metal sleeve with a very low emissivity. Another possibility is that uneven flow distribution is not a serious issue in solar collector fields, which would explain why it was not possible to detect it. If this is the case, then drone thermal imaging could potentially work, though its application would not be very useful since the problem does not seem prevalent.

Pit thermal energy storage

The second application that was investigated in this project was detection of leakages and thermal bridges in pit thermal energy storages (PTES). PTESs are large water reservoirs where hot water from e.g. solar collector fields can be stored for weeks or months. To limit the heat losses, the reservoirs are covered with a floating insulated lid. Since this technology is still relatively immature (there are only six such storages world wide), a number of issues with leakages and high heat loss through the lids exists. This can be seen from the performance measurement from the storage operation, but locating the exact location of the issue, is challenging due to the large surface area of the lids.

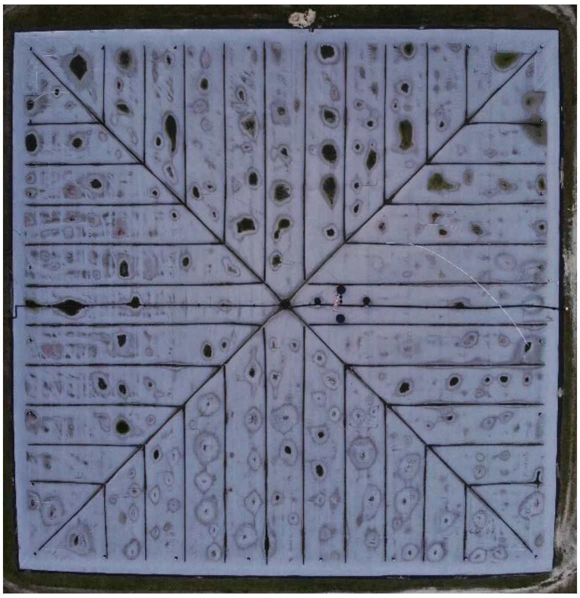

Figure 4. Aerial photo of the PTES lid in Dronninglund.

Four different PTESs were investigated in this project, located in Dronninglund, Vojens, Gram, and Toftlund. The first storage that was investigated was the storage in Dronninglund, with a surface area of approximately 10 000 m^2: 100 by 100 meters. Figure 4 shows a regular image of the storage, which is helpful when trying to make sense of the thermal images. For example, when detecting a hot spot in the thermal equivalent image, it is important to crosscheck the RGB image and make sure that the hotspot is not due to a piece of debris or different surface material.

In total 272 thermal images were taken of the storage in Dronninglund from an altitude of 25 m.

These images were stitched together to form a large overall image, called an orthomosaic, which is shown in Figure 5. In this image, the entire storage lid is visualized and many temperature variations are seen. One of the most noticeable observations was the many warm oval shapes on the lid. When comparing the locations and shapes of these to the RGB image in Figure 4, it can be seen that these are water puddles that have formed on the lid. The reasons that they are detected as warmer than the adjacent areas is that the emissivity of water is higher than that of the lid surface. However, the temperature of the puddles can be compared with each other, and it can be identified that the puddle in the top left corner of Figure 5 is warmer than the rest of the puddles. After conferring with the local plant manager, the warmer puddle was inspected further, and it was found that the lid had been penetrated in this area and warm water from the storage was entering the lid. After it was located, the leak was fixed, which in turn had a positive impact on the storage performance and lifetime of the insulation.

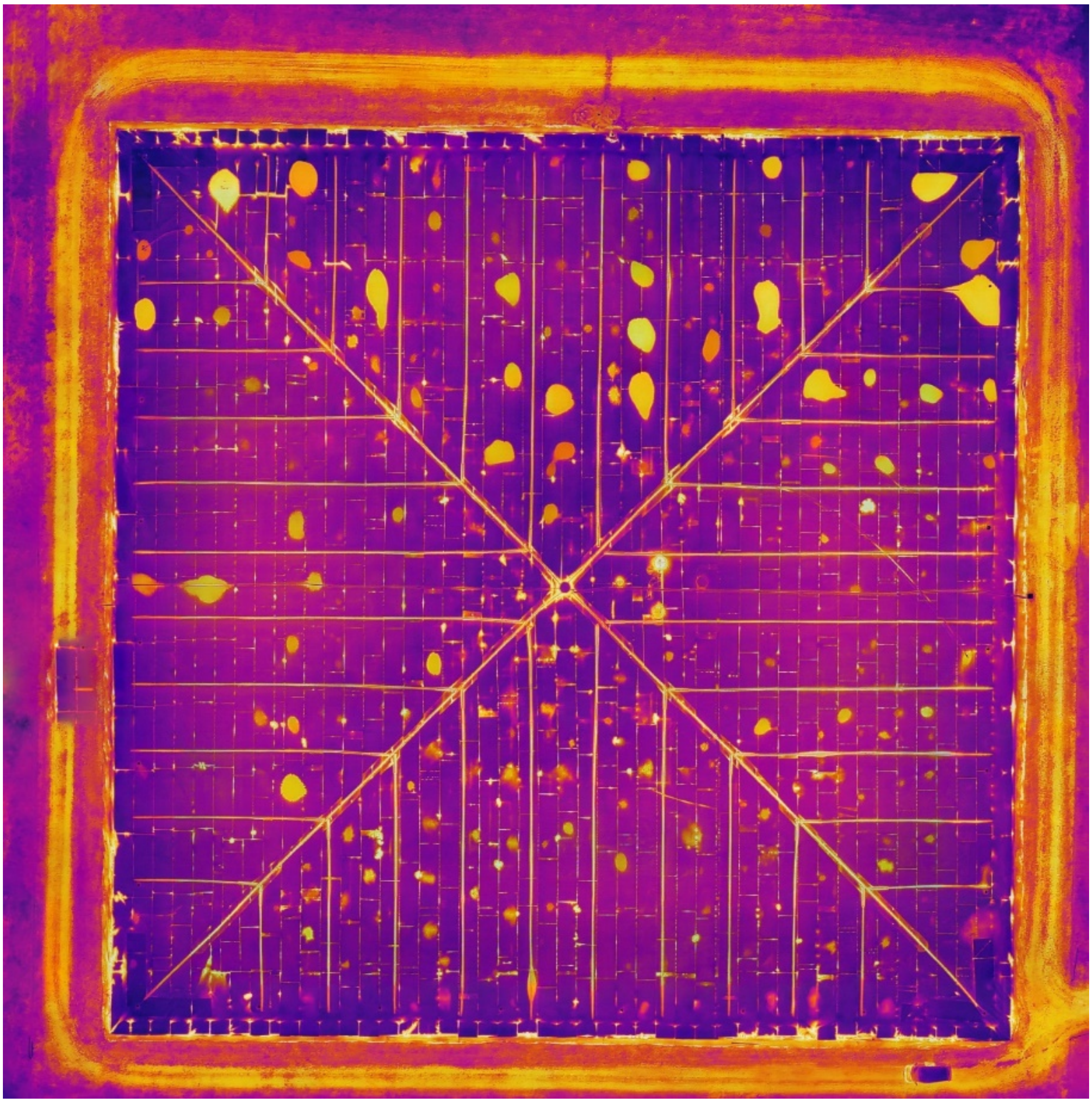

Figure 5. Thermal orthomosaic image of the PTES lid in Dronninglund.

The diagonal lines in Figure 5, also seen in Figure 4, are not due to temperature differences, but are weight pipes that have different surface emissivity than the rest of the lid. The smaller vertical and horizontal gridded lines in Figure 5, however, are not seen in Figure 4. This signals that they are indeed thermal bridges, corresponding to the spacing between the individual insulation elements inside the lid. If possible, for future pit storages, the spacing between the insulation elements should be reduced or better linkage should be made between the insulation layers.

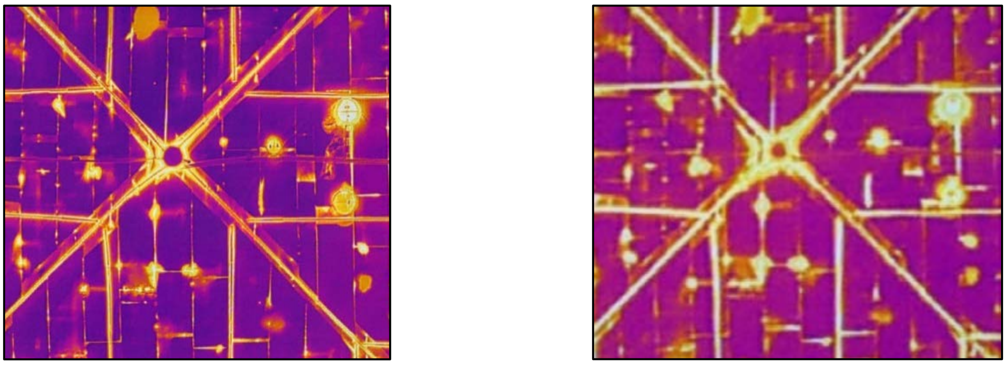

Figure 6. Comparison of the center part of the Dronninglund storage from 25 meters altitude (left) and 80 meters altitude (right).

The inspections at the Dronninglund pit storage were done at two different altitudes of flight: 25 meters and 80 meters. When the altitude is lower, the captured images are more zoomed in, which means that the flight paths need to be closer and more images need to be captured. For the Dronninglund pit storage, that meant that for the higher altitude 91 images were captured, whereas for the lower flight path a total of 272 images were taken. The resulting orthomosaics are compared in Figure 6. While they are essentially the same, the image quality for the lower flight path is much higher and the details are much clearer. This is to be expected as it consists of three times as many images and required much more time and battery during flight.

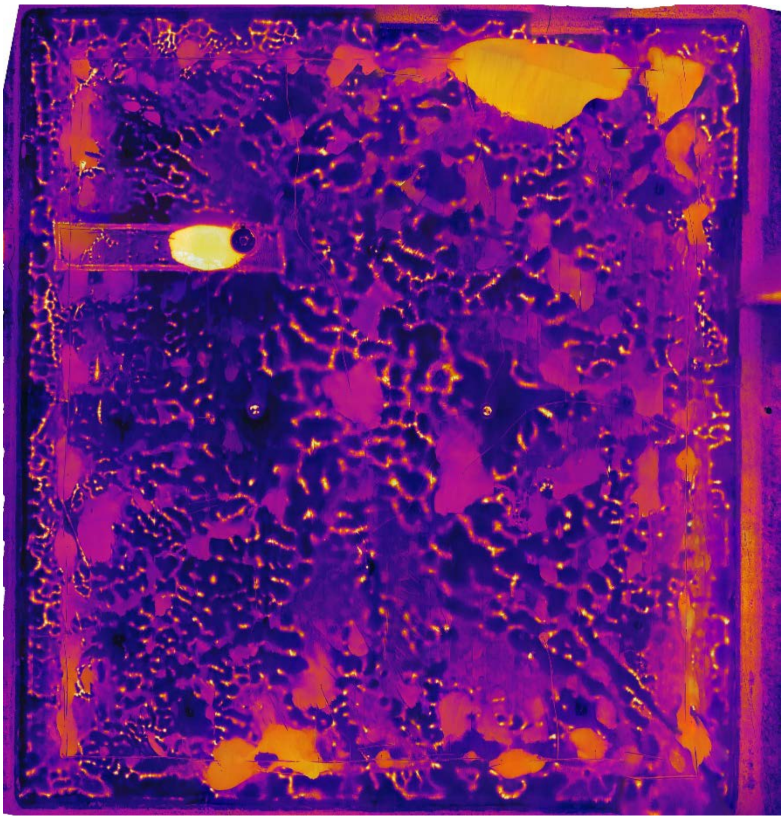

Figure 7. Thermal orthomosaic of the Gram PTES.

The orthomosaic for the PTES in Gram is shown in Figure 7. This image looks vastly different then that of the PTES in Dronninglund in Figure 5. The reason for this is due to the different insulation materials used within the PTES lids. In Dronninglund, rectangular insulation mats were used, which clearly could be seen in Figure 5 from the thermal bridges due to the spacing between the mats. For the PTES in Gram, as well as Vojens and Toftlund, the insulation material used was expanded clay balls. The brain-like pattern visible in Figure 7 is therefore thought to be due to convection within the lid. Convection within the lid should be minimized as much as possible, as it enhances the thermal losses from the storage. As the image clearly illustrate, there is some form of thermal bridges, most likely due to convection. It is suggested that either smaller clay pebbles should be used in the future or a convection membrane is installed.

For the Gram PTES in Figure 7, it was also possible to identify a significantly warmer puddle on the lid, indicating a leak. This information was provided to the district heating plant manager, who then went on to conduct manual inspection at the located point.

Discussion

While the project was not successful in detecting the effect of possible uneven flow distribution in three solar collector plants, it elucidated that this technology is most likely not suitable for such investigations due to the reasons discussed. However, for the investigation of pit thermal energy storage lids, the thermal drone orthomosaics led to a number of unique discoveries. These included locating of a warm pool on the Dronninglund lid, which was found to be caused by a leak. The leak was quickly fixed, thereby increasing the thermal performance of the storage and extending the lifetime of the insulation material. Furthermore, a potential leakage was also discovered for the PTES in Gram. Both of these discoveries were unknown to the plant owners prior to the drone investigations, and proved the technology to be successful in locating otherwise difficult to find leaks. All in all, the project led to a number of significant discoveries, including dissemination of best practices and thermal drone recommendations to a number of district heating plants as described in the following section.

Dissemination

The project was presented at the 5th International Solar District Heating Conference 2018 with an abstract and poster presentation titled "*Use of drones to evaluate the thermal performance of solar collector fields"*. The project was later presented at CleanCluster's Drone workshop in December 2018. Furthermore, the project results have been disseminated in the form of orthomosaic thermal images and performance feedback to numerous district heating companies, including the district heating plants in Silkeborg, Dronninglund, Gram, Vojens, Toftlund, and Høje Taastrup Fjernvarme. Also, the project methodology and images were presented at the annual Pit Thermal Energy Storage Follow-up meeting in Aarhus on October 23rd, 2019.

References

DeWitt, David. et al. 2011. Fundamentals of Heat and Mass Transfer, 7th Edition. John Wiley & Sons.

Lanz, Manuel. 2015. Infrared (IR) drone for quick and cheap PV inspection. 31st European Photovoltaic Solar Energy Conference and Exhibition.

Scheuerpflug, Hans. 2014. Field inspection of PV-module using aerial, drone-mounted thermography. 29th European Photovoltaic Solar Energy Conference and Exhibition.

Vadhavkar, Nikhil. 2017. Best Practices for Making a Radiometric Orthomosaic (Thermal Map). https://raptormaps.com/thermal-map-best-practices/. Accessed June 4th 2019.

FLIR. 2019. UAS Radiometric Temperature Measurements. https://www.flir.com/discover/suas/uas-radiometric-temperature-measurements/. Accessed December 9 2019.

OPGAL. 2018. Introduction to IR (Part 1): The physics behind thermal imaging. https://www.opgal.com/blog/thermal-cameras/the-physics-behind-thermal-imaging. Accessed on December 5 2019.

DTU
Department of Civil Engineering
Technical University of Denmark

Brovej, Building 118
2800 Kgs. Lyngby
Tlf. +45 45 25 17 00

www.byg.dtu.dk
ISBN: 87-7877-526-4