Master's thesis – master Energy Science

Hotspot testing of a shade resilient smart photovoltaic panel

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Abstract

To be able to prevent some future natural disasters for nature, wildlife and humans reduction of greenhouse gases is needed as these are the source of human-induced climate change. The energy sector is one of the main emitters of the two most important greenhouse gases: methane and CO2. Electricity for buildings and the industry are large sources of these. Solar photovoltaic is an interesting alternative and renewable option for electricity production. However, hotspots from partial-shading are currently a major problem for PV panels as these lower electricity problems and can result in damage of the panel. Many techniques are tried or currently applied, but hotspots are still occurring. By Golroodbari et al. (2019) an alternative PV panel structure was proposed in which the PV cells are optimized per group of ten instead of per module or per multiple modules. In this research the module is tested wired smart or in series to be able to make a comparison.

Two setups were made: one using halogen lights and one using LED lights to lower the chance that the light source was reason for certain test results. Tests endured multiple hours and an infrared image was made every five minutes to check the module for hotspots. Also the I and V data were measured for further analysis if hotspots occurred. Furthermore, a comparable module was tested to exclude the option of no hotspots occurring due to the adjustments made to make the PV module smart.

A total of 10 hotspots were found spread over two test round which were both in series. No hotspots were found in the smart PV panel test rounds. However, the irradiation intensity for both test setups was not very high with a maximum of 340W/m2. But, as hotspots occurred in this research it is expected that this did not affect the test results. So, it can be concluded that the smart PV panel proposed by Golroodbari et al. (2019) is hotspots resilient under indoor testing conditions. Additionally, recommended follow-up research would be outdoor testing, but current results are already expected to result in market interest.

Table of Contents

1. Introduction

Human-induced climate change has to be reduced to prevent natural disasters which affect nature, wildlife and humans. Climate change currently leads to droughts, wildfires, floods and other extremes. For this, the emission of greenhouse gases (GHGs) like carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) has to be reduced (IPCC, 2021). CO2 and CH4 are the most emitted GHGs and so, these are important for tackling climate change (Olivier & Peters, 2020). The energy supply sector is currently one of the main sources of emissions and this is expected to continue. Electricity for buildings and the industry sector is known to be an important reason for this (IPCC, 2014). Therefore, more sustainable electricity sources are needed. Solar photovoltaic (PV) electricity is currently a major source which is expected to continue in the future (IEA, 2019, 2021). PV panels are continuously being improved to increase output per panel, but production loss is an important problem (Fouad et al., 2017a).

Especially hotspots induced by partial shading are seen as a major problem occurring in PV panels (Olalla et al., 2018). When an object is partially shading a PV cell will result in a higher resistance of that specific cell, as the current will be lower due to less irradiance. As solar cells are connected in series, the current will continue to go through this shaded cell. The current through this cell results in heating of the cell because of the high resistance (Ramaraj et al., 2015). Prevention of hotspots induced by shading is a problem which needs to be addressed. Hotspots result in damage to the solar cells and lower power output (Hwang et al., 2021; Muñoz et al., 2008). Many mitigation techniques are found that can partially solve this problem, like more bypass (BP) diodes, shingle PV modules, half-cell modules, BP diode, ideal diode combination and more other techniques. However, none of these techniques are currently seen as a solution to the partial shading problem. The addition of many BP diodes is seen as a solution, but adding more BP diodes is seen as a very costly solution (Vieira et al., 2020). Moreover, shading is a problem for maximum power point trackers (MPPT) in a system, as partial shading affects the normal curves which affects the efficiency of the MPPT algorithm. Traditional MPPTs are programmed to find the maximum power point for normal power-voltage (P-V) curves, but as partial shading changes the curve, new algorithms or other techniques have to be found to solve this problem. There is a lot of research being done on this topic, but no optimal solution has been found yet (Ahmed & Salam, 2015; Liu et al., 2015).

A solution for hotspot creation on PV panels was proposed by Golroodbari et al. (2019). To solve the partial shading problem the amount of MPPTs installed on a PV module was increased together with active BP diodes instead of passive BP diodes. The smart panel was first simulated in Matlab, which showed good results. Then, the panel was tested under real world conditions, but only for one hour. The results showed that the power output under partial shading could be 5.1 times the output of conventional modules with only three BP diodes for hotspot prevention under the same conditions (Golroodbari et al., 2019). Testing for longer periods is necessary to prove this. Therefore, the research question (RQ) of this paper is: “Does the newly developed smart photovoltaic module from Golroodbari et al. (2019) prevent the occurrence of hotspots from shading?”.

To answer this the smart panel was tested in a lab at the Hogeschool Utrecht. During the measurements partial shading was created which would normally result in hotspots. The appearance of hotspots was the main indicator whether the panel is shade resilient. Temperature measurements were done using infrared (IR) thermography. The results were compared with the same panel, but wired in series as if it was a conventional module. Moreover, different light sources were used and also a similar panel was tested for comparison of the panel. It was expected that the smart panel would result in a lower amount of hotspots, but would not exclude the possibility of hotspots.

Firstly, the concepts that were used in the Golroodbari et al. (2019) paper were elaborated which includes clarification of some terms that were used. Secondly, the methods were explained including why these were used. Thirdly, when the data from the panels was acquired, this was compared and analysed. Next, all results were compared to existing literature and uncertainties in the results were explained. Part of the existing literature for comparison was another master thesis, in which the thermal performance of the smart panel was simulated (Ayyad, 2021). The compared results created an extensive review of the performance of the smart module, and so, It was possible to make more reliable conclusions. Also, a discussion was included which addresses potential problems or uncertainties of the research. Solutions were included to prevent these problems and raise certainty of the results. Furthermore, relevance of the results was included to put the results in perspective. Lastly, a reference list was added to make all information trackable to its source.

2. Concepts

2.1. Passive infrared thermography

Passive infrared thermography is the detection of radiation from an object or surface in the IR spectrum to create an image (Williams, 2014). As a solar cell heats up and the partially shaded cells heat up more, this IR technique can be used to detect hotspots. Actual hotspot temperature measurement will allows to gain understanding of their intensity as well (Hwang et al., 2021).

2.2. Smart module

The smart module is an optimised silicon PV module from Golroodbari et al. (2019) in their research. This module was designed by her, and so, it is no factory standard module, but built by an external company using her design. She researched the options for module integrated electronics (MIE) on a PV module to reduce the effects of shading on module performance. This resulted in some specific module architecture details. Firstly, the total of sixty cells in the module were divided in groups of ten with DC-DC buck converters connected to each group of cells. This was done to improve performance when current levels decrease by compensating it. The converters are computed via a sampling-based method of a sweep method maximum power point tracker (SM-MPPT) algorithm. The sampling frequency is 1.4kHz. The addition of a MPPT for every group enhances the performance by mitigating the effects of partial shading, and so, should reduce the amount of hotspots. The electricity production should increase in this way as no groups are bypassed, which normally results in no electricity production from that specific group at all. Therefore, this method should decrease losses from partial-shading. Additionally, the wiring of all cells to a connection point on the panel is done in such a way that the length of every wire is equal. In order to exclude the option that differences are measured per cell due to differences in resistance from various wire lengths. Furthermore, the board of the module is custom built, and so, there are no more detailed device specifications on this.

2.3. Optimizer

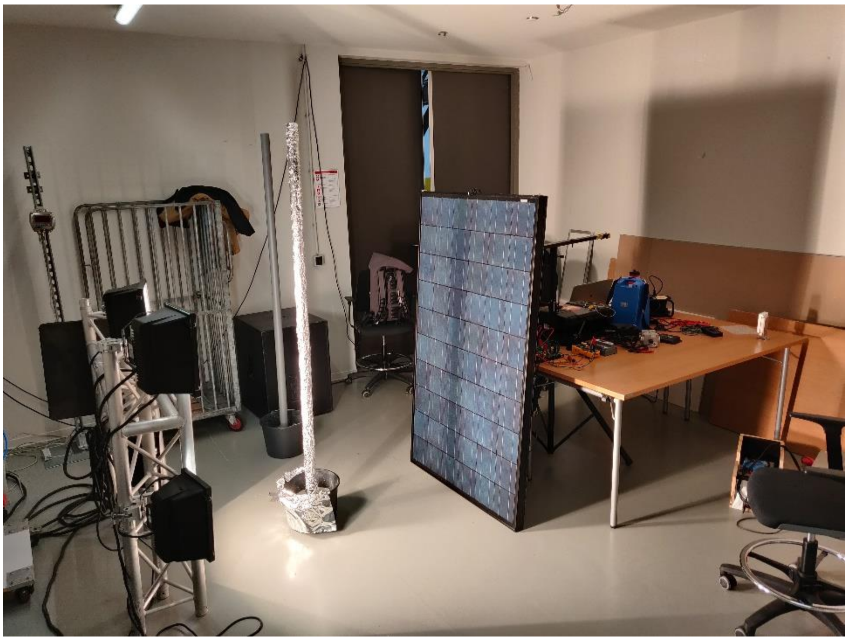
A maximum power point tracker (MPPT) or optimizer is a device connected to a PV system or panel to optimize the voltage and current to reach the maximum power production possible.

3. Methodology

3.1. Physical setup

The module was tested at the Hogeschool Utrecht. The lab has experience in research on sustainable energy production and the development of technologies which could be of use for this research. Furthermore, there was room and equipment for physical testing of the PV panel and adjusting (Hogeschool Utrecht, 2022). Therefore, this location and its facilities were very useful for physical indoor testing of a PV panel. Also, there was equipment to make adjustments if needed to the setup or to do a quick repair if something was broken.

Figure 1: Smart PV panel setup with construction lamps for light.



The first setup of the solar panel was built by using four 1000W (halogen) construction lamps mounted at aluminium truss systems. The four construction lights consisted of three construction lights EUROLUX 1000W and one ELRO HL710 1000W. These were used based on availability at the Hogeschool Utrecht. These were mounted in a square in such a way that the long side of the lamps was directed vertically as shown in Figure 1. This way, the panel was illuminated more even. The panel was placed against a standard under an almost 90 degrees angle compared to the ground. Hence, the light came onto the panel at nearly 90 degrees. The lamps were placed at 1.3m distance from the panel. The IR camera was placed at such a distance that the full panel was visible, but no reflection from the lamps was seen as this would change the measured temperature. The panel was first tested as smart panel, where the Arduino was attached to a laptop to constantly send data. This data was directly being saved using Python in a way that all V, I and P data is separately stored in Excel files. The Arduino script and Python script can be found in the supplementary material. This was used to prove the occurrence of hotspots if these were seen on the IR images. A resistor of 1 Ohm was placed in parallel between the circuit board from Golroodbari et al. (2019) and the panel to smoothen the electricity flow. The used resistor is: ARCOL HS100 1R F. A PVC pole was placed in a plastic bucket to create shade on the panel. The bucket was filled with concrete to keep the pole up. The pole was wrapped in aluminium to prevent the PVC from melting from the heat of the lamps. As shading is never perfect in real-life situations, the pole was placed 0.66m from the panel to cause some light to pass the pole.

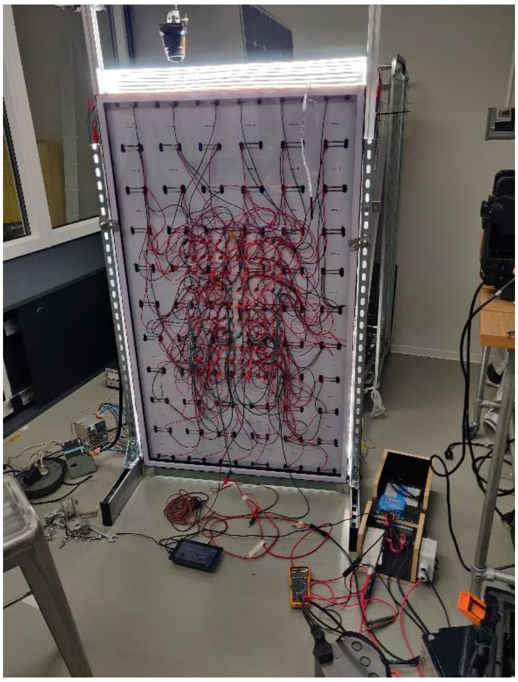
To show whether the non-existence of hotspots was due to the smart setup of the PV panel, it had to be tested as if it was a regular panel. For this, the panel wiring was reorganised to connect the cells in series again. This panel was then connected to an optimizer. This created a normal situation where the panel was still optimized for power production, but per panel instead of per group of cells. The optimizer used is: Victron Energy blue solar charger MPPT 70/15. Additionally, a battery was connected to act as load dump. This enabled a flow to continue to run as the panel creates current. As batteries degraded during testing for an unknown reason, various batteries were used based on the availability of the Hogeschool Utrecht. In test rounds 8, 9 and 10, an attempt to solve the problem of degrading batteries was made by connecting a desk lamp or a small construction lamp to the battery. This was done to improve the use of produced electricity to solve the problem of degrading batteries. However, this did not result in a difference. This setup was again tested with the construction lamps for four hours. The current and voltage was measured every 5 minutes using a multimeter manually as the Arduino was not connected anymore. It was not possible to connect the smart setup in series on the smart board, because the voltage would increase too much.

Furthermore, to exclude the option that the panel was not able to produce hotspots for unknown technical reasons in the (smart) panel itself, another similar panel was tested as well. The alternative panel used was: Ubbink 180wp monocrystalline silicon of ten years old. The specific model is unknown. It was connected to the same setup as the in series connected smart module and tested similarly for an hour.

3.2. LED setup

To exclude the option that the halogen lights resulted in no hotspots due to the amount of infrared it radiates, a LED setup was build which can be seen in Figure 2.

Figure 2: LED test setup wired in series.

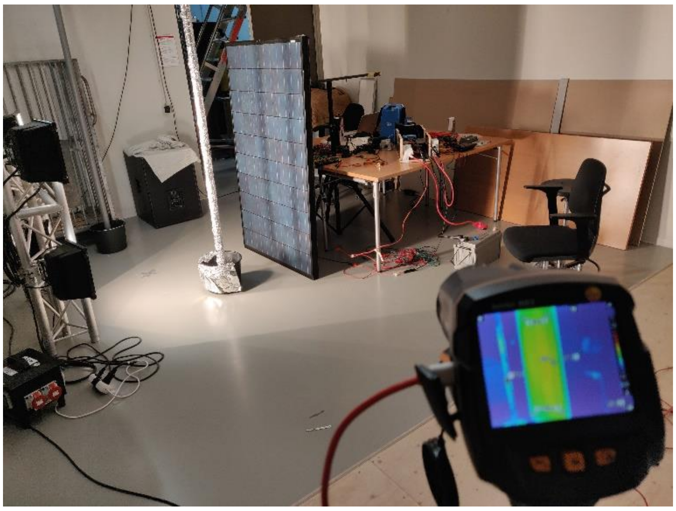


For this, 26 LED strips with each 512 LED’s per meter and five meter per strip were glued to an aluminium panel of 1m×1.6m×0.0015m. The aluminium panel in combination with the aluminium structure worked as a heat exchanger to get rid of the excess heat from all the lights. All LED’s resulted in 130,000 lumen. Due to limited availability of high powered LED’s, a combination of light colours was used. Sixteen COB LED strips of 6000K, four of 4000K and six of 3000K were used. The aluminium was folded on the sides to maintain as much light as possible so most light would reach the panel. All wiring was divided into different power sources due to low availability of power sources that can handle more than 60A. The IR camera was hung above the setup to make images. The panel was put at a distance of roughly 20 centimetres away from the lights in an aluminium frame. For every image that was made with the IR camera, the hinges were temporarily unscrewed and the picture was made while the panel would be slightly tilted. For the smart setup the same smart board was connected with the PV panel as for the setup with construction lights. The same holds for the in series setup. Additionally, the LED setup was tested in a different room which was roughly a third of the size of the room used for the construction light setup.

Figure 3: Example of the object for creation of shadow on the PV panel. In the figure it is hanging on against the panel during one of the test rounds.

For the creation of a shadow, a plastic package was wrapped in aluminium foil which could roughly shade one cell. To this, a electrical wire was attached and wrapped in aluminium foil as well. In this way the object could be moved over the panel and hanged on top of the panel using the metal wires that could create a hook that would stay in place on the edge of the panel. The object can be seen in Figure 3.

Figure 4: Point-of-view of the IR camera for making images for first four test rounds.



An infrared (IR) camera was placed in front of the panel. An example from the construction lights setup can be seen in Figure 4. The thermal imaging camera that was used is the Testo 883. This camera was able to make an IR image simultaneously with a normal and was able measure the temperature with a precision of 0.1 K. Therefore, it was possible to analyse the thermal images in detail afterwards. This camera was adjusted in height in such a way that no shadow was created on the modules and no light reflection was seen.

During all the tests using the construction light and LED setup randomly the temperature of the smart PV panel was measured. This was done to check for differences using a connection in the middle of the panel which was connected to a Vernier thermocouple. The thermocouple was connected to a LabQuest2 to check whether the PV had a unexpected high temperature compared to the images. If this was the case it was noted. Furthermore, to gain insights in the irradiation of the testing setups, the irradiance was measured in the middle of the panel and in the corners. The highest and lowest temperatures were noted. These measurements were done using a Solarimeter SL200.

3.3. Data collection

To test the panel a standard scheme of testing was used. First, the panel circuit was reconnected as this was disconnected between test runs. Second, the Arduino was attached to a laptop to be able to run again as it needs a power source. Third, the construction lights were switched on to illuminate the panel. Then, the temperature of the room was measured in case unexpected results were occurring. If these occurred then these measurements are used for further discussion of the results. Next, the lights and panel were working without any data collection for 20 minutes, as previous test runs showed that this period the temperature of the panel increased quickly. After this period, the testing started. An IR picture was made, the Python script was started to save the I, V and P data and the temperature was measured again. The I, V and P data was measured and saved 100 times per second. The IR picture was taken every 5 minutes and the temperature was noted roughly three times during the test round. A whole test round lasted four hours. For creating different test versions, the pole was replaced to the middle of the panel at the same distance as before. After this the pole was placed against the panel on the right. This was with the panel still in smart setup. After this, another test round was included in which the pole was placed back in the same way as the first round and put in series for comparison.

The LED setup was tested mostly in the same way as the previous setup. However, due to time constraints the test round time was lowered to two hours instead of four. Also, no start-up time was included in which the lights were already switched on before measurements started. This was specifically not done in case this could increase the chances of hotspots in the period where the panel was still cold.

For comparison, the thermal images were analysed using IRSoft v4.8 which is made for the Testo camera used. In this program the image is placed next to the normal picture. This made it usable to see whether there was something in the picture which affects the specific image like a dust spot on the lens or something similar. Also, it was possible to see the temperature in the program at every point. This increases the trustworthiness of the analysis as this was done besides only looking at the picture for colour differences in the picture. In the results not every picture was shown, but random for three moments per test run. In case hotspots or other irregularities were found these images were shown. Adding all images would not have shown more information. Added to the three IR image a normal image is added for overview of the setup of the Test run. For making an image looking for a hotspot two images were made. One image was made with the object for shadow in place and one image was made when this object one was moved aside temporarily. On top of the panel a line was present. This line was used as marker to move the object back in the same place every time. The test was done with the object in place in front of the last cells in a lower corner and another round in front of the same cells but halfway up the panel. An overview of all tests done is shown in Table 1.

Table 1: Overview of all tests with its specifications and abbreviation. Abbreviations are Construction lamps (C), test number 4 (4), In series setup (IS) and Custom panel (C) which leads to C4ISC.

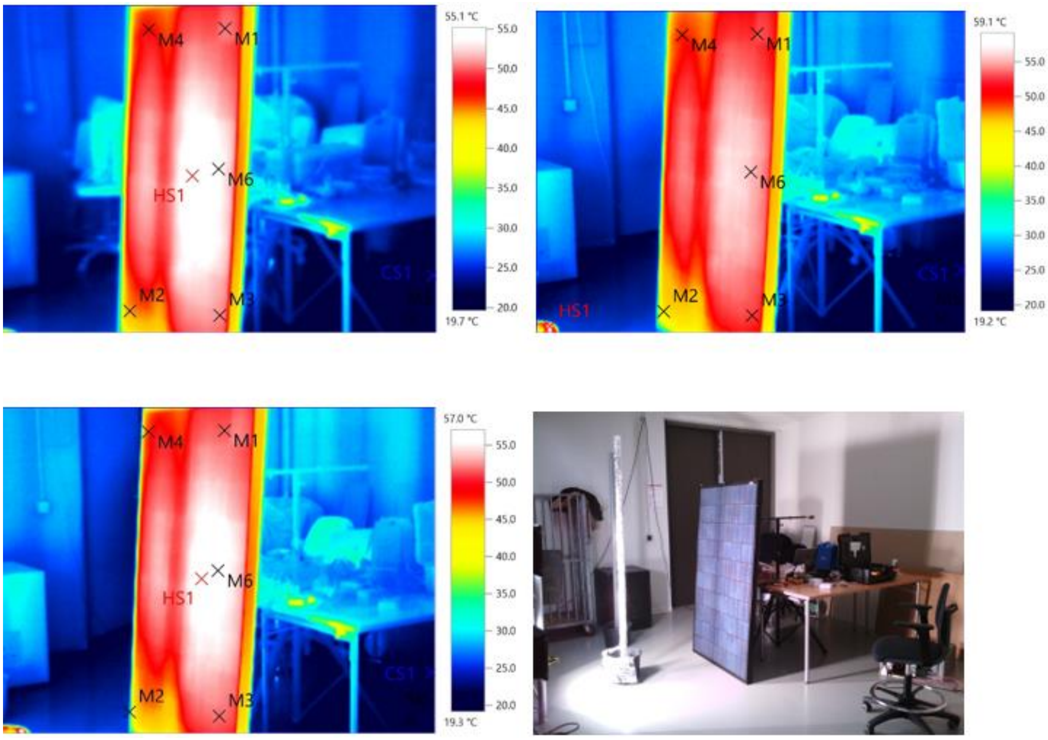
Light source	Test number	Setup (smart/in series)	Panel (Custom/Factory)	Abbreviation
Construction lamps	1	Smart	Custom	C1SC
	2	Smart	Custom	C2SC
	3	Smart	Custom	C3SC
	4	In series	Custom	C4ISC
LED	5	In series	Custom	L5ISC
	6	In series	Custom	L6ISC
	7	In series	Custom	L7ISC
	8	Smart	Custom	L8SC
	9	Smart	Custom	L9SC
	10	Smart	Custom	L10SC
Construction lamps	11	In series	Factory	C11ISF

The images whether hotspots occurred was the main indicator. All I, V and P data will be measured using the Arduino Due which was already used for controlling the smart panel and the data was input data per cell. This would result in large amounts of data. Therefore, the data was processed in Python. Python is better at handling large amounts of data than for example Excel. Also, if done right the chances of mistakes in Python was smaller as it was expected that less manual actions are needed to process the data. I, V and P data was analysed to investigate the effect of hotspots on them. If hotspots occurred it was expected that this would be seen in this data as values would lower for the specific cells.

4. Results

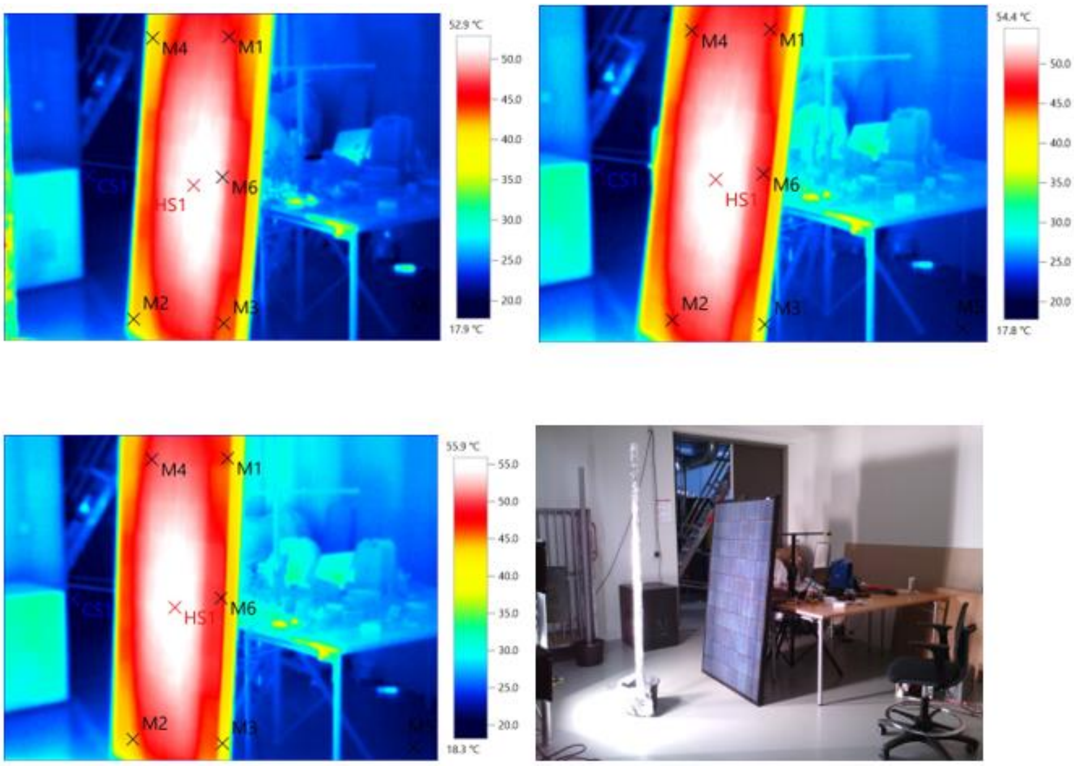
In the following figures you can see IR images and normal images of all test rounds. In the images the colours are based on the spectrum seen in the picture. This was adjusted automatically by the camera and the range can be seen on the right. Furthermore, the M1, M2 and so on are points in which the temperature was specifically shown in the data in IRSoft. However, these were not added as the picture is self-explanatory due to the colour overview.

Figure 5: Overview of Test C1SC showing three IR images and one normal image. Note: legends next to images are different.



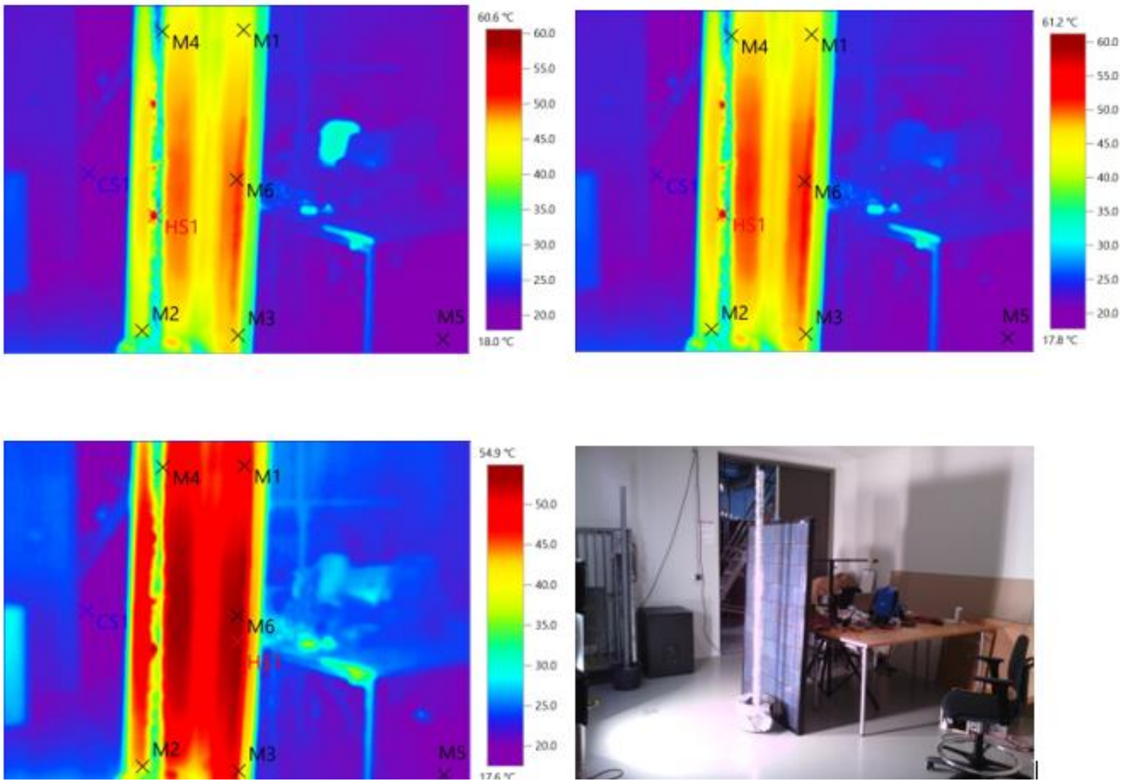
Looking at Figure 5. it can be seen there are no small areas with a much higher temperature in the shaded parts of the panel. The parts that are shaded have a lower temperature. Furthermore, it can be seen that especially the shade of the bucket creates a large area with lower temperatures than its surroundings. In these shaded parts the panel is cooler than the shaded parts of the pole. Also, the temperature diffences of the panel can vary roughly 10 °C in the non-shaded parts and almost 20 °C between the shaded and the non-shaded parts.

Figure 6: Overview of Test C2SC showing three IR images and one normal image. Note: legends next to images are different.



From Figure 6. it can be seen that there are shaded parts of the panel heating up more than its surroundings. It looks like that the shaded part on the left side of the panel is lower. However, the center of the panel has a higher temperature than the edges. Also, the shaded part on the right side of the panel is not showing the same temperature difference. So, it is unclear whether the temperature is lower due to shading of the bucket and pole. It looks like the shaded parts have a temperature range of nearly 10 °C while the difference between the non-shaded parts and the shaded parts reach up to 15 °C.

Figure 7: Overview of Test C3SC showing three IR images and one normal image. Note: legends next to images are different.



In Figure 7. it can be seen that the panel is cooler in the shaded part except for in the middle of it. However, looking at the normal image it can be seen that the positioning of the lamps leads to two shades from the pole as it is placed near the panel. This explains the hotter part. Also, below on the images a small red dot is seen. However, looking closely at the normal image it can be seen that this spot is not the panel, but the bucket. Furthermore, the differences in temperature within the shaded parts can reach up to 15 °C and the temperature difference of the non-shaded parts can be up to 20 °C higher compared to the shaded parts.

Figure 8: Overview of Test C4ISC showing three IR images and one normal image. Note: legends next to images are different.

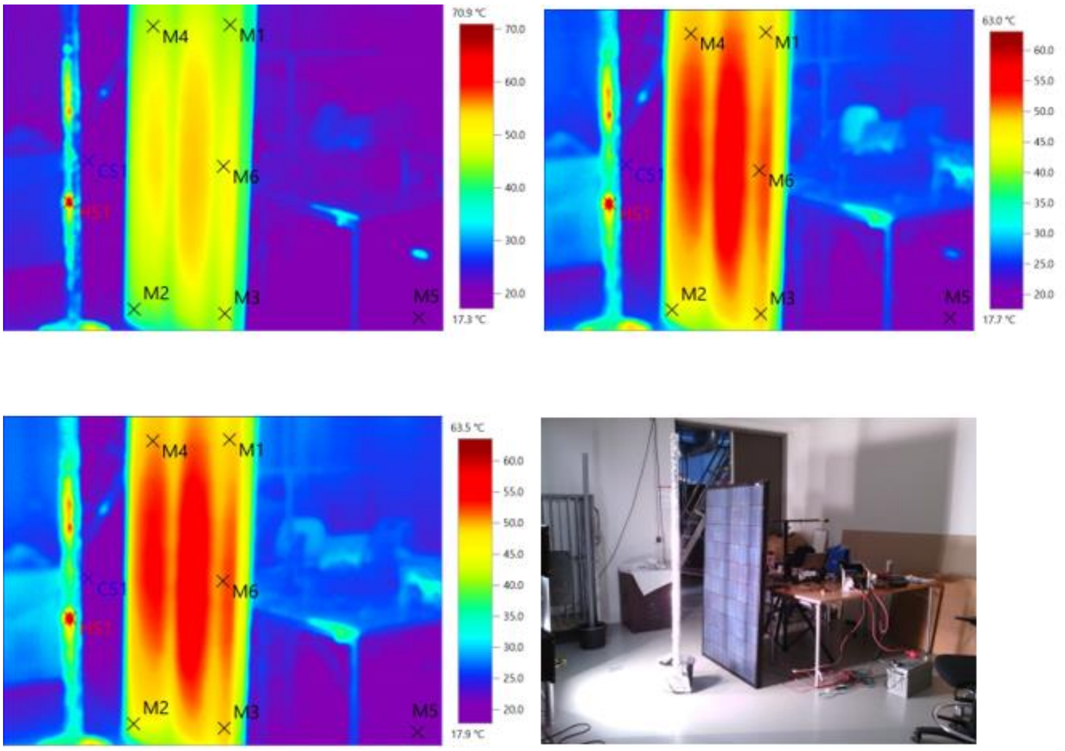
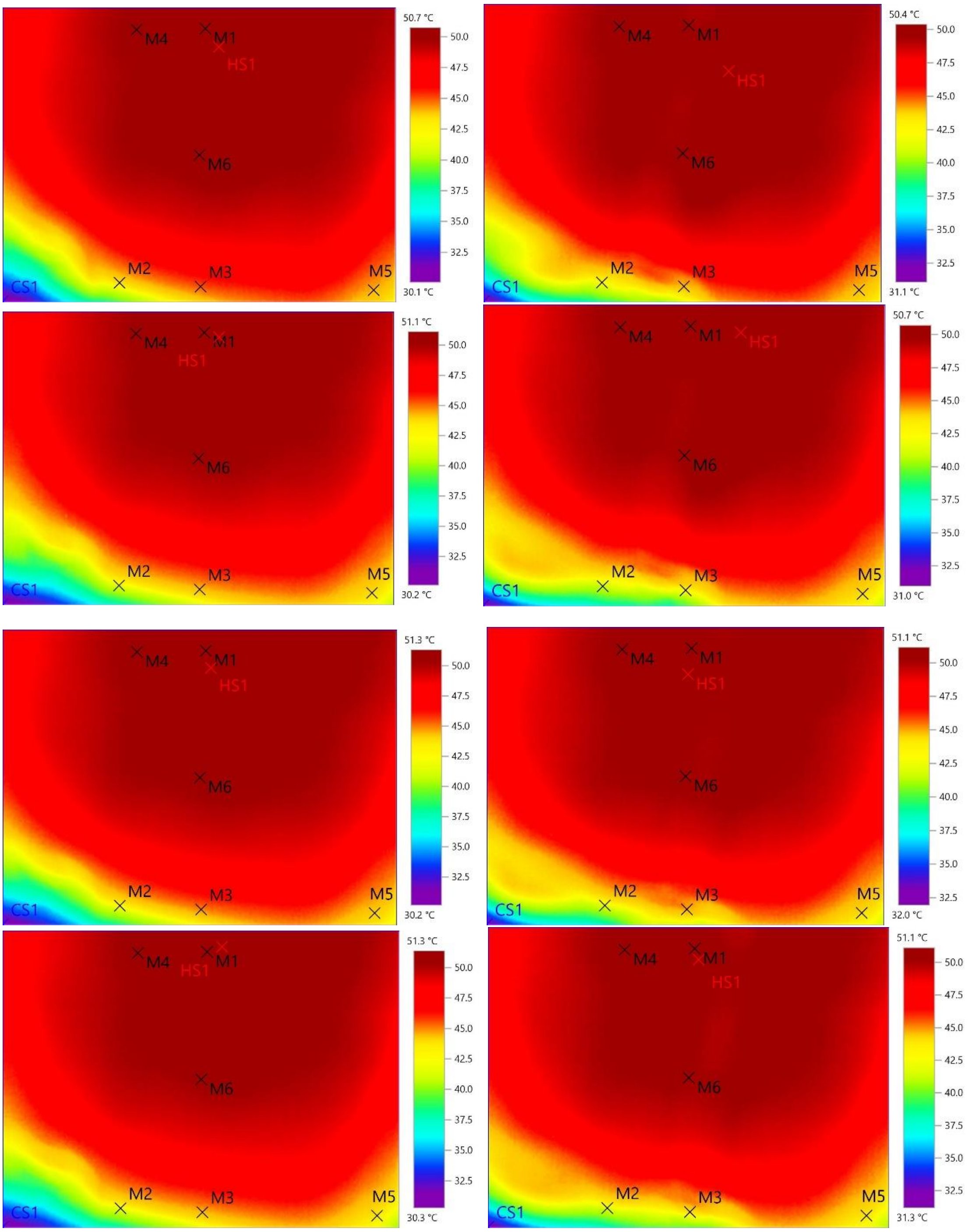
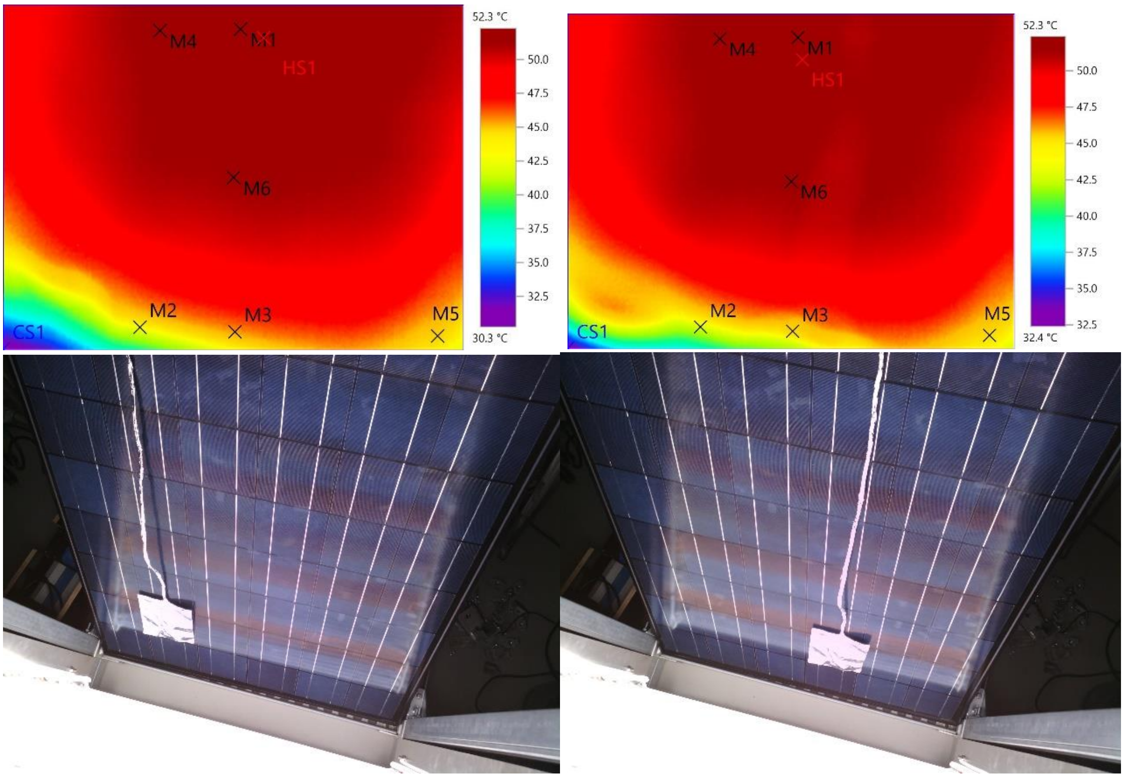


Figure 8. shows no points with much higher temperatures within the shaded areas. The shaded areas have a lower temperature than the non-shaded parts with a difference of up to 15 °C. The differences within the shaded parts reach up to 10 °C. Also, the images show that two shades are created due to the positioning of the construction lamps.

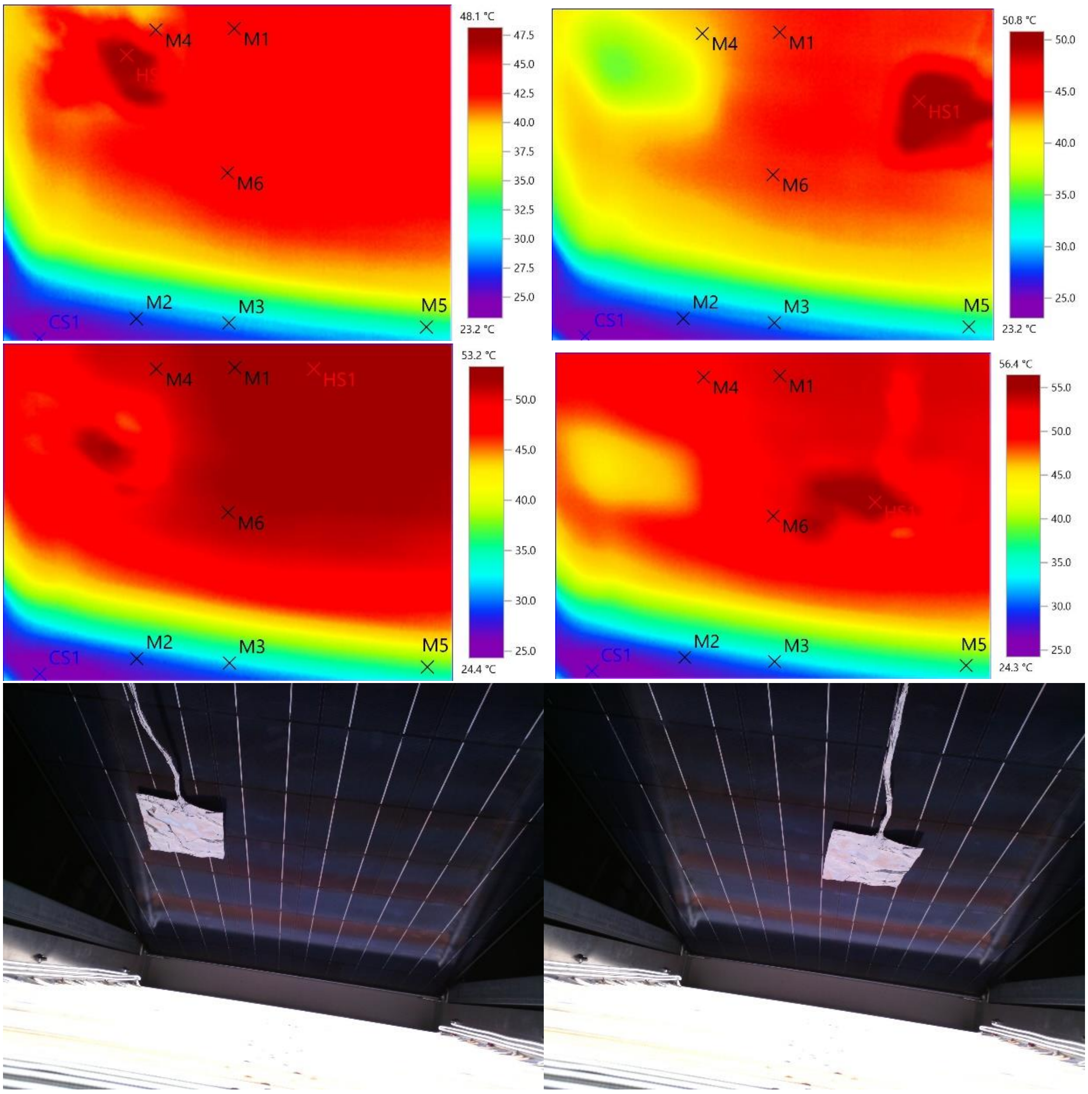
Figure 9: Overview of Test L5ISC showing all images with a potential hotspot. In the images on the left the object is in place and on the right the object is moved to the right. The last two images show the normal images. Note: legends next to images are different.





In Figure 9. five potential hotspots are seen in the down left corner. In the images on the left with the object in place to make shading it can be seen that the parts are lower in temperature in the particular place compared to those spots of the image on the right. A part is red while its surroundings are still yellow. This could be a hotspot. However, in the I-V data, which can be found in the supplementary material, no large differences are seen. Moreover, the temperature difference within the shaded parts reach up to 7.5 °C. The difference between the shaded parts compared to the non-shaded parts reached up to 10 °C. Lastly, it can be seen in some of the images on the right that some shade is created on the panel by the wire which is attached to the object for shade. However, no effects on the panel are seen in the images on the left from long term exposure to such an amount of shading. The lower temperature is only seen in the pictures in which the object is removed for examination of the shaded parts.

Figure 10: Overview of Test L6ISC showing two moments checked for hotspots. In the images on the left the object is in place and on the right the object is moved to the right. The last two images show the normal images. Note: legends next to images are different.



In Figure 10. no hotspots are seen in the shaded parts when the object is removed for analysis of the shaded parts. In the images on the left a large hot area is seen with a higher temperature than its surrounding. But, looking at the images on the right the hot area moves when the object is moved. Furthermore, the shaded parts can differ up to 5 °C with its surroundings and the temperature of these parts can be up 10 °C lower than the non-shaded parts.

Figure 11: Overview of Test L7ISC showing all images with a potential hotspot. In the images on the left the object is in place and on the right the object is moved to the right. The last two images show the normal images. Note: legends next to images are different.

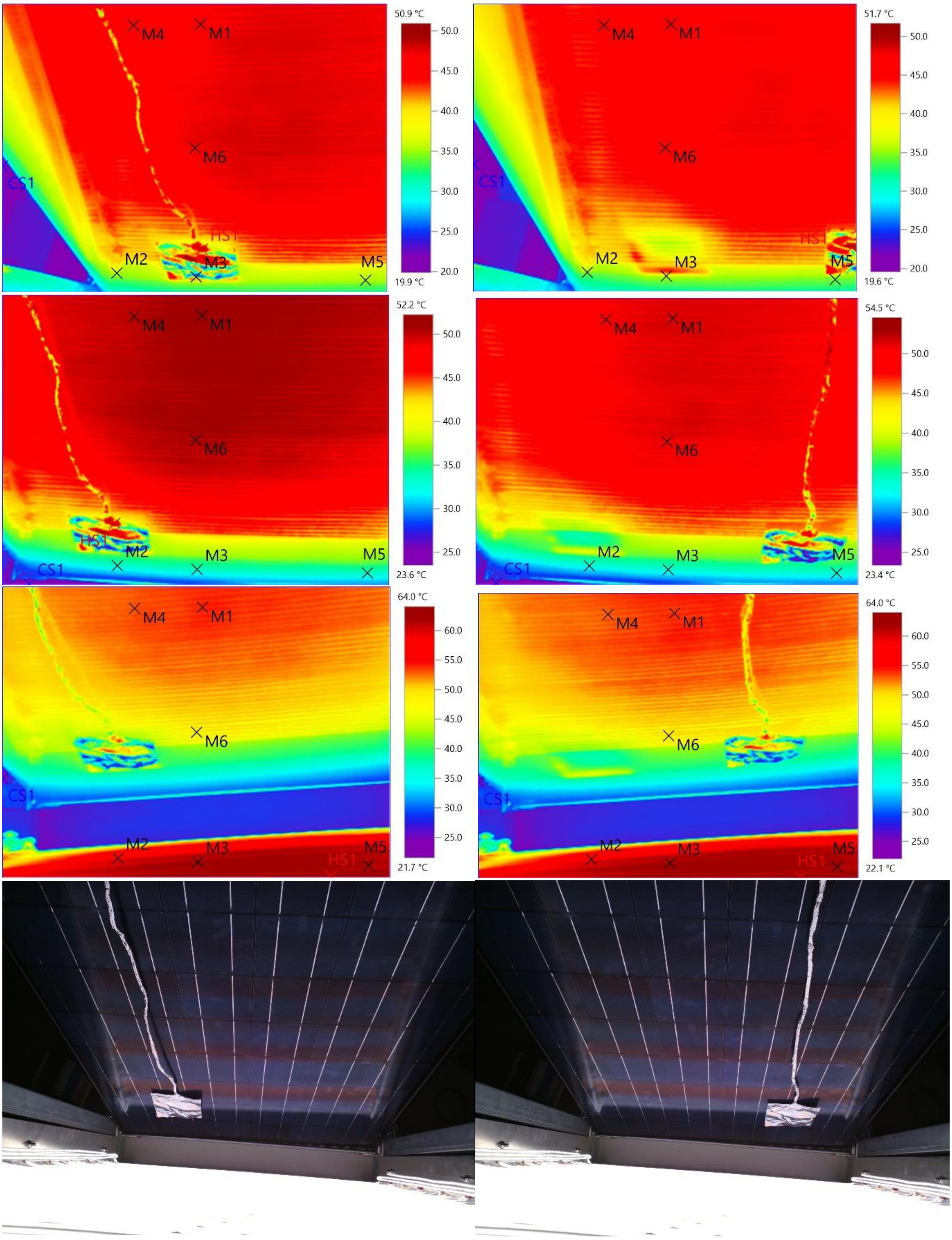
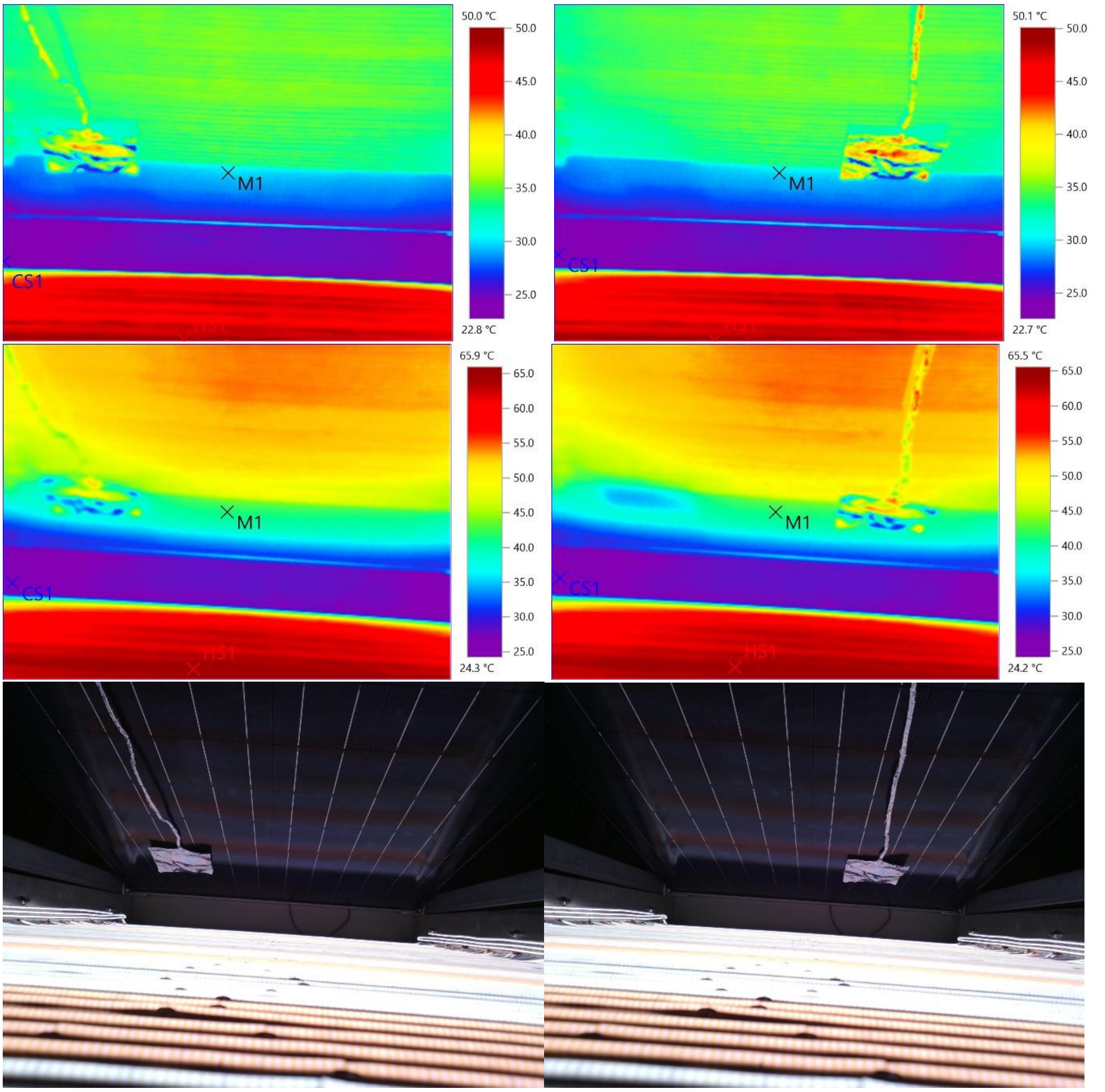


Figure 11. shows three potential hotspots on the sides of the shaded parts with higher temperatures than its surroundings. Comparing these parts with the normal images it can be seen that the object for shading is bent slightly in the corners where the hotspots occur. However, the temperature is still much higher than its direct non-shaded surroundings. The shaded parts do not always show temperatures which are the same or higher than the hottest

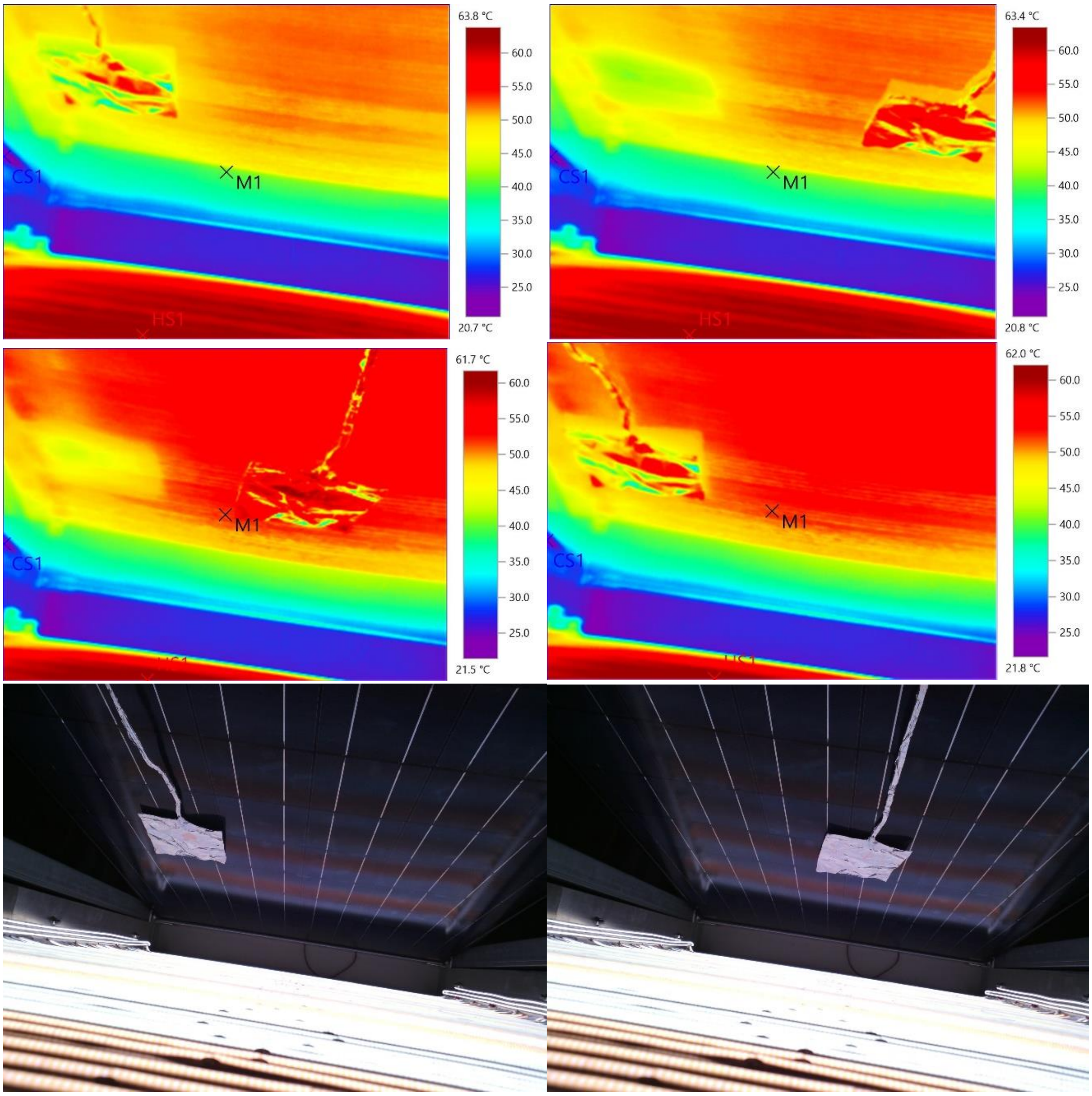
parts of the whole panel. However, this effect is seen on the whole lower end of the panel. The temperature difference of these parts can reach up to 10 °C with the other shaded parts and up to 15 °C with its direct surroundings which is not shaded. Moreover, the temperature difference between the shaded and non-shaded parts can reach up to 20 °C. Lastly, the moments which are shown as images containing potential hotspots are not seen in the I-V data as a large difference compared to all other data points in test round 7.

Figure 12: Overview of Test L8SC showing two moments checked for hotspots. In the images on the left the object is in place and on the right the object is moved to the right. The last two images show the normal images. Note: legends next to images are different.



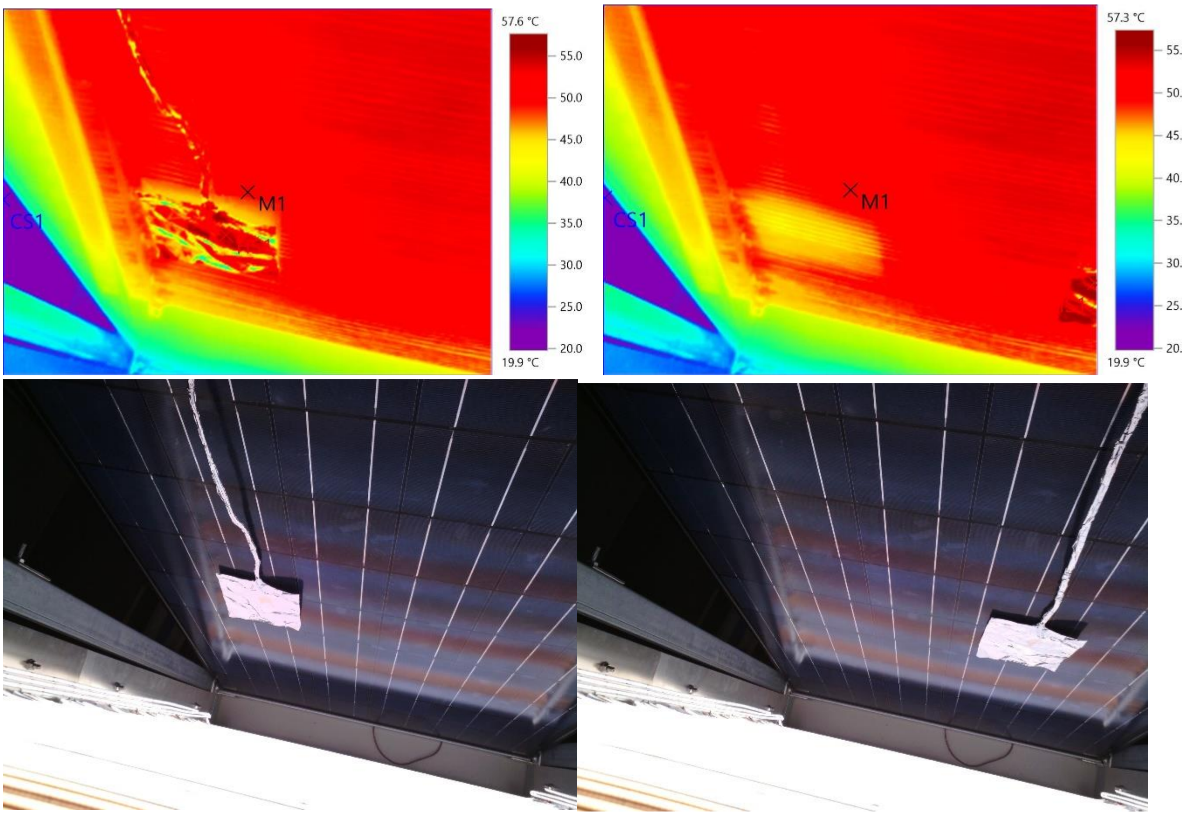
The two moment of all images of test round 8 which can be seen in Figure 12. show no potential hotspots in the shaded parts. All shaded parts are colder than its surroundings with a temperature difference within the shaded parts up to 10 °C Celsius. The temperatures of the shaded parts can be up to 20 degrees Celsius lower than the non-shaded parts of the panel. Furthermore, a large difference in temperature can be seen between the first two images and the second two. The second two images are later in the test round than the first two. Also, there are small intense red spots seen in the images. However, looking at the normal images it can be seen that these spots are on the object for shading and the wire attached to it. When this was moved the hot parts moved with it.

Figure 13: Overview of Test L9SC showing two moments checked for hotspots. In the images on the left the object is in place and on the right the object is moved to the right. The last two images show the normal images. Note: legends next to images are different.



In the two moments checked for hotspots from shading in Figure 13. no spots with higher temperatures are seen compared to their surroundings. The shaded area was always colder than its direct surroundings. Only at the lower end of the panel a lower temperature is measured. However, from the normal images it can be seen that less light reaches this area. On the contrary, it cannot be seen whether the temperatures measured are only the panel itself or also the heat reflection of the LED lights. Furthermore, the temperature differences within the shaded areas reach up to 5 °C and the non-shade parts are 10 to 15 °C lower than most of the panel. Only the lower end of the panel is colder. Also, hot and cold spots are seen in the images with a much higher temperature than its surroundings. However, comparing these images with the normal images it can be seen that these are heat reflections from the object.

Figure 14: Overview of Test L10SC showing all images with a potential hotspot. In the images on the left the object is in place and on the right the object is moved. The last two images show the normal images. Note: legends next to images are different.



In Figure 14. a potential hot area is seen at the lower end and the top right of the shaded area. It is not hotter than the surrounded non-shaded part, but a higher temperature is measured compared to most of the shaded part. Comparing this with the normal images the object is slightly bent and more light can pass compared to the other shaded parts. Additionally, this part has the same temperature as its non-shaded surroundings. The difference within the shaded parts can reach up to 10 °C and these parts can be up to 15 °C lower than the non-shaded parts. One picture on the right shows parts with higher temperatures in the lower right corner of the image, but comparing this with the normal images it can be seen that the object for shading shows these temperatures.

Figure 15: Overview of Test C11ISF showing three moments checked for hotspots. In the images on the left the object is in place and on the rigth the object is moved. The last two images show the normal images. Of all images the left image is of the top of the panel and the right image the bottom of the panel. Note: legends next to images are different.

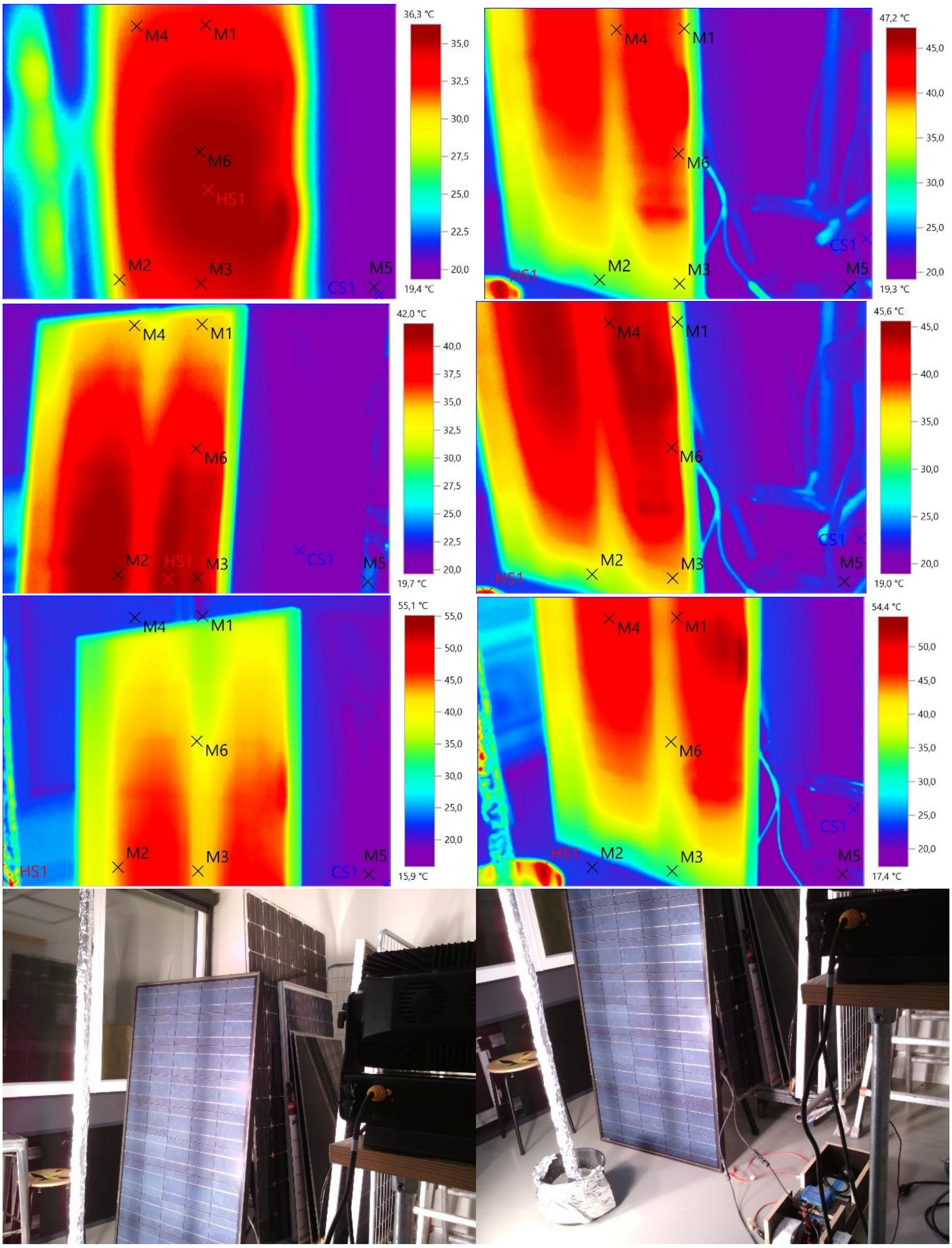


Figure 15. shows no hot spots in the shaded areas. In the normal images it can be seen that there are two shaded areas from the pole. Within the shaded areas the temperature difference can be up to 10 °C. Also, the temperature in the shaded areas can be up to 20 °C lower than the non-shaded areas. In the non-shaded areas on the right end of the panel areas are seen with a higher temperature than its surroundings, but comparing this with the normal images it looks like these are reflections of the construction lamps on the panel.

Figure 16: Temperature difference of the PV panels for every test round

Test round	Temperature difference within shaded area (°C)	Temperature difference between shaded area and non-shaded area (°C)
C1SC	10	20
C2SC	10	15
C3SC	15	20
C4ISC	10	15
L5ISC	7.5	10
L6ISC	5	10
L7ISC	10	20
L8SC	10	20
L9SC	5	15
L10SC	10	15
C11ISF	10	20

Comparing all test rounds for hotspots a few things can be noticed. Firstly, hotspots are only found in the test rounds in which the panel was in series and the LED board was the light source. Secondly, the hotspots did not always occur while conditions were not changed much between some test runs. Thirdly, the comparison with another panel showed that no differences in terms of hotspot creation are found using the construction lamps between the in smart panel, the panel in series, and the comparable panel. Additionally, the amount of pictures shown with potential hotspots shows the low occurrence of these spots as most round contained up to 36 pictures and less than ten moments in total are found containing potential hotspots. Furthermore, there are no large temperature differences between test rounds seen when comparing all temperature differences of the PV panel seen in Figure 16.

Comparing the testing conditions it can be seen that the construction lamps lead to less even distribution of heating of the panel. Also, comparing all normal images from those test rounds the amount of lighting is also not evenly distributed over the panel. Furthermore, the images were not always sharp in every test round. Additionally, the setup with a pole in a bucket for shading compared to the object hanging lead to much more shading on the whole panel. This resulted in large cold areas behind the bucket and sometimes multiple shades.

5. Discussion

To start with, the results show a comparable outcome to the modelled testing of (Ayyad, 2021). The results showed no hotspots with high temperatures which strengthens the outcome on hotspots resilience of the smart panel from (Golroodbari et al., 2019). The conditions are different than modelled in the research of (Ayyad, 2021). Therefore, the researches are complementing each other, and so, their results as well. Further real life research in outdoor conditions are an interesting next step. This could be potentially lead to market interest in the new PV panel structure outside of the companies which were initially involved with the development of this smart PV panel: Heliox and Kameleon Solar.

Besides, application of the new panel structure to new PV panels also can lead to increased safety of PV panels as hotspots can result in extreme conditions in fires as the heat can act as source of ignition for nearby materials (Pandian et al., 2016). This could also improve trust in PV as alternative electricity source if chances of fires decrease, and so, potentially increase demand.

The testing had some limitations which could be changed or solved in future research. To start with, some images in which the hotspots are seen are relatively unsharp compared to all IR images. This makes the results less trustworthy. However, the hotspots are very clear and exactly in the shaded area. So, the chance of those spots really to be hotspots is high. Moreover, hotspots were also seen in test round L7ISC in which the images are sharper. Additionally, it looks like that the hotspots in the less sharp images are still hotter than its direct non-shaded surroundings which increases the chance that these areas have an increased temperature from being shaded, and so, being hotspots.

Secondly, the comparison with a comparable PV panel showed that the creation or missing of hotspots is not expected to be due to the adjustments to the PV to make it smart. This increases the trustworthiness of the results as it lowers the chance of no hotspots to be shown from technical issues from adjustments. However, this was only checked using the construction lamps and not with the LED's where hotspots were shown. In future research a comparison with another panel with other lights than the construction lamps could make the exclusion of this chance more impactful.

Thirdly, the images made and moving the object for the LED setup had to be done manually. Doing things manually is expected to make things less accurate compared to doing things automatically. This lowers the accuracy of the measurements, and so, the results. However, larger amount of measurements increase the accuracy of the average outcome. Therefore, it is expected that the results are reliable.

Also, it was seen in the results when comparing the IR images with the normal images that the construction lights did lead to no uniform irradiation of the PV panel. This could potentially be a reason for no hotspots in those test rounds as there was light from four directions instead of one. This could be of impact as the shading was not very close to the panel to create real world conditions in which some diffuse light is occurrent as well. However, potentially the four sources of light led to too low amount of shading, and so, to too small difference between shaded and non-shaded parts for hotspots to be created or able to see in the IR images. Moreover, part of the light from both light sources is IR which heats up the panels. So, besides heating up from electricity production the panels directly heats up from radiation. This was seen in the results in which the shadowed parts had a lower temperature. It was expected that the LED lights would heat up the panel less as this type of lights produce less heat. However, the panel did not decrease clearly in temperature. So, it is unclear whether the heating from light affected the results as outside solar irradiance also heats up the panels, but no comparison was made with this type irradiance. This is something to take into account for further research or can be an interesting new research subject. Also, it can be a reason for further research to be done in real life conditions.

Figure 17: Spectral distribution of the LED lights used

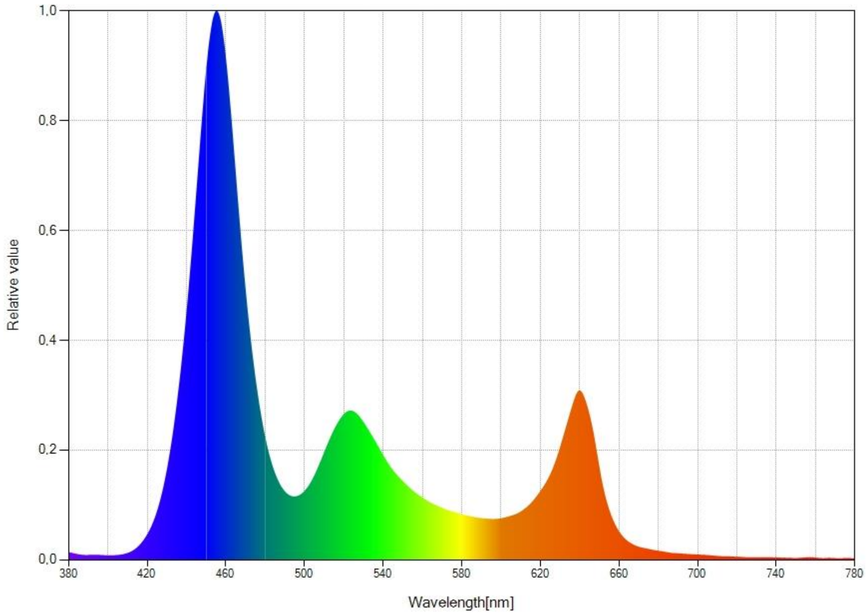


Figure 18: Spectral distribution of the used construction lights

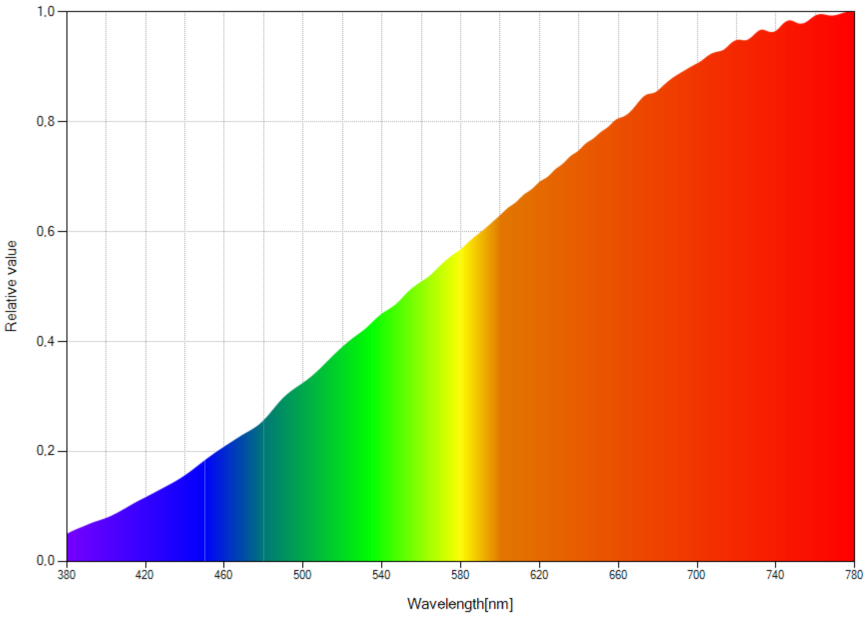
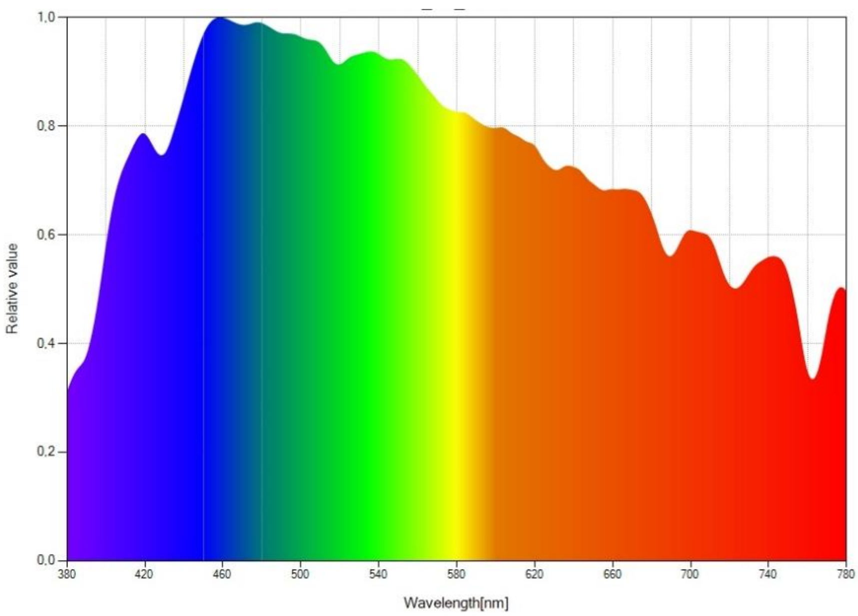


Figure 19: Spectral distribution daylight measured from behind glass



For better understanding of the testing conditions the spectral distributions of the LED's and the construction lights were measured using a spectrometer. From inside, and so, through a window, daylight was measured on a partial cloudy day. Figure 17., Figure 18. and Figure 19. showed that the spectrum of artificial lighting, both LED and incandescent, is very different from normal daylight. For the LED colours the 4000K, 5000K and 6000K lights were used to match daylight colours. However, the spectrometer results showed that this is still different from natural light. The used PV panels used are silicon based PV. The part of the light spectrum from which these kind of PV panels absorb light most efficient is around 590nm wavelength. This is less available in both artificial light sources (Chander et al., 2015). The difference between the optimal spectral distribution and the artificial light is expected to lead to lower electricity production, and so, lower occurrence and intensity of hotspots. Therefore, it would be interesting for follow-up research to test the smart panel setup or something similar under normal daylight.

For both setups the irradiation was measured to get an idea what the intensity was. For the construction lights the highest irradiation intensity was measured in the middle of the panel with 340W/m2 and on the sides the lowest intensity measured was 140W/m2. As the difference from the middle to the sides went fluently it is expected that this did not affect the results. In the LED setup the irradiance was almost even and had a light intensity of around 250 W/m2. Both light intensities were not low. So, the expectation is that the hotspot intensity was lower than otherwise. However, as hotspots appeared it is expected that the amount of hotspots would stay the same. Therefore, it is expected that results were not different, but further research would be interesting to include standard testing conditions of around 1000W/m2.

Moreover, the current panel setup needed much wiring as can be seen in Figure 2. This results in high losses due to high resistance. Further research is needed how to optimally design the smart structure for decrease of energy losses. Also, these losses are expected to have resulted in lower chances of hotspot creations and lower hotspot intensity. However, it is not expected that this had large effect on the results as the setup made every cell comparable and there were hotspots appearing in the in series setup.

Also, improvement for the Arduino code in the future could be a time constraint on optimizing. This could be done by increasing the time per period after which a new optimum is searched if a certain amount of steps are within a limited range of power production. As this would mean the Arduino is near its optimum this could lower the amount of calculations that are needed to be made, and so, reduce the power needed for the Arduino. This could lead to a reduction of energy losses. Also, the Arduino produces heat. Reducing the amount of calculations that are needed can result in lower heat production. This is good for the PV panel performance as the efficiency of a PV panel lowers with increasing temperature (Dubey et al., 2013).

Furthermore, for unknown reasons part of the images from test round 11 from the first 35 minutes are lost. It is assumed that this would not affect the results as all known images are in line with results from other test rounds using the construction lamps and this round was for comparison. However, the conclusion that the custom panel is performing as a normal panel is less trustworthy due to lower amount of data from the normal panel.

Also, the battery degradation and connection of lamps to potentially solve this problem results in differences per test round in the setup. However, the voltage was sometimes checked during all test rounds to check the battery and no structural changes were measured. Therefore, it is expected that this has not resulted in different results. So, it is expected that this did not affect the trustworthiness of the results.

Then, the smart module is custom built which increases the chances of irregularities. It is not expected that this will affect the results, but it creates some uncertainty compared to high volume manufactured modules.

Lastly, an important issue which resulted in some missing moments to make an IR image was the trustworthiness of the IR camera. The battery could be drained faster later testing rounds than the first few for unknown reasons. For this reason test round 5 could not be finished twenty minutes early. For other test rounds the camera could freeze for an unknown reason. The camera had to be removed from the setup and restarted. This took a few minutes, and so, resulted in a few missing images. However, it is expected that this only led to a lower amount of data, and so, did not affect the results. Only a few images were missed which made the amount of missing images less than 5%, and so, insignificant.

6. Relevance of the results

As hotspots can damage PV panels (Muñoz et al., 2008) the smart panel can lead to a lower amount of operation and management (O&M). This could be interesting for companies as it lowers the amount of time that has to be spend on PV systems to keep working and lower the amount of money spend on this. Also, if one of the potential problems that damage PV panels is solved this increases the reliability of PV systems and it is expected that with this also the total electricity per panel increases. Studies show that electricity production can decrease up to 1 or 2% from hotspots (Fouad et al., 2017b). Solving this could reduce these electricity losses. These benefits are expected to create interest from the market in the new PV panel structure. Especially for floating PV, as also mentioned in (Golroodbari, 2021), shade resilient PV panels are interesting.

An interesting area for these smart PV modules to be placed is between windmills as their rotor blades create shadows on the panels. Furthermore, operation and maintenance in offshore solar can be up to 25% of the total costs over its lifetime (TNO, 2022). In The Netherlands this technology could be attractive to make use of as the Dutch government aims to create large scale offshore wind farms which results in a large usable area for electricity production in between of wind mills (Rijksoverheid, 2022). Therefore, the technology could enhance the introduction of floating PV as complementing offshore electricity production technology for The Netherlands and potentially for other countries as well.

Another example technology for which a hotspots resilient PV module is expected to be an interesting innovation is building-integrated photovoltaics. As in this kind of PV it is integrated in building parts it is expected that repairs have higher costs and are more time or labour intensive. Therefore, this could be an interesting field for the new PV structure as well.

Furthermore, the results suggest that the smart panel is hotspot resilient which creates options for potential higher power production per year per panel as a smaller part of the panel has been adjusted instead of bypassing a part of the PV panel. So, more cells of the module could produce normally over a year, and so, the panel produces more. Additionally, less panels are expected to need replacement or repairs due to hotspot damage which lowers the need for new panels. This could lower PV panel demand if this smart structure would be standardized for all or most PV panels. It could therefore be a solution for production to keep up with global electricity growth from renewable electricity sources. Also, if demand would grow less due to the new PV panel structure widespread application this could result in a lower growth in demand for resources. It is unclear how much resources are needed in the future to make new panels smart, but there is a chance this would lower the negative impact of PV electricity production from resource use as less repairs or new panels are needed. This could be interesting for making PV electricity a more sustainable electricity source in the future.

However, future research is needed to show future potential of the new PV panel structure. The PV panel market is highly competitive and if costs are higher than the benefits it is unsure whether the technology will be applied. If the panel results in lower resource use this could lead to special interest as sustainability of products also has its worth, but costs are expected to remain the most important factor. Current research only shows whether it works and not what the way of optimal performing could be.

7. Conclusion

To be able to keep up with the energy transition for a sustainable future more renewable energy is needed from which electricity from PV is an major source. Improvements could accelerate this increase in electricity generated from this source of electricity. An important problem for PV panels is currently partial shading as this can result in damage and lower production due to hotspots. However, by Golroodbari et al. (2019) a new smart panel is developed which optimises power production not per panel but per group of cells, but this panel structure had to be tested for longer periods than one hour. So, it was unknown whether the new smart panel was hotspot resilient. The results show a few hotspots in the IR images in which the panel was not smart and only one image shows a potential hotspot when the panel was smart. However, the last mentioned hotspot was expected to be from a mistake in the test setup. Furthermore, all hotspots were not seen as disturbances in the measured I-V data, but this can be caused by the low light intensity of the testing conditions. Therefore, it can be concluded that the new smart panel concept works under indoor testing conditions using halogen or LED lights. For further steps in the development of this smart panel it is recommended to test the panel under outdoor testing conditions.

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9. References

Ahmed, J., & Salam, Z. (2015). A critical evaluation on maximum power point tracking methods for partial shading in PV systems. *Renewable and Sustainable Energy Reviews*, *47*, 933–953. https://doi.org/10.1016/J.RSER.2015.03.080

Ayyad, A. (2021). *Simulating a Prototyped Smart PV Module for Thermal Performance*.

Chander, S., Purohit, A., Nehra, A., Nehra, S. P., & Dhaka, M. S. (2015). A Study on Spectral Response and External Quantum Efficiency of Mono-Crystalline Silicon Solar Cell. *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH Subhash Chander et Al*, *5*(1).

Dubey, S., Sarvaiya, J. N., & Seshadri, B. (2013). Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review. *Energy Procedia*, *33*, 311–321. https://doi.org/10.1016/J.EGYPRO.2013.05.072

Fouad, M. M., Shihata, L. A., & Morgan, E. S. I. (2017a). An integrated review of factors influencing the perfomance of photovoltaic panels. *Renewable and Sustainable Energy Reviews*, *80*, 1499–1511. https://doi.org/10.1016/J.RSER.2017.05.141

Fouad, M. M., Shihata, L. A., & Morgan, E. S. I. (2017b). An integrated review of factors influencing the perfomance of photovoltaic panels. *Renewable and Sustainable Energy Reviews*, *80*, 1499–1511. https://doi.org/10.1016/J.RSER.2017.05.141

Golroodbari, S. Z. M. (2021). *The Sun is rising over the North Sea - Assessment of offshore solar photovoltaics*.

Golroodbari, S. Z. M., Waal, A. C. de, & Sark, W. G. J. H. M. van. (2019). Proof of concept for a novel and smart shade resilient photovoltaic module. *IET Renewable Power Generation*, *13*(12), 2184–2194. https://doi.org/10.1049/IET-RPG.2018.6127

Hogeschool Utrecht. (2022). *Smart Sustainable Cities: werken aan de slimme, duurzame stad | Hogeschool Utrecht*. https://www.hu.nl/onderzoek/coe-smart-sustainable-cities

Hwang, M.-H., Kim, Y.-G., Lee, H.-S., Kim, Y.-D., & Cha, H.-R. (2021). A Study on the Improvement of Efficiency by Detection Solar Module Faults in Deteriorated Photovoltaic Power Plants. *Applied Sciences 2021, Vol. 11, Page 727*, *11*(2), 727. https://doi.org/10.3390/APP11020727

IEA. (2019). *World gross electricity production by source, 2019 – Charts – Data & Statistics - IEA*. https://www.iea.org/data-and-statistics/charts/world-gross-electricity-production-by-source-2019

IEA. (2021). *Renewables – Global Energy Review 2021 – Analysis - IEA*. https://www.iea.org/reports/global-energy-review-2021/renewables

IPCC. (2014). *Climate change 2014 : mitigation of climate change : Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

IPCC. (2021). *Climate Change 2021 Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Summary for Policymakers*.

Liu, Y. H., Chen, J. H., & Huang, J. W. (2015). A review of maximum power point tracking techniques for use in partially shaded conditions. *Renewable and Sustainable Energy Reviews*, *41*, 436–453. https://doi.org/10.1016/J.RSER.2014.08.038

Muñoz, J., Lorenzo, E., Martínez-Moreno, F., Marroyo, L., & García, M. (2008). *An Investigation into Hot-Spots in Two Large Grid-Connected PV Plants*. https://doi.org/10.1002/pip.844

Olalla, C., Hasan, Md. N., Deline, C., & Maksimović, D. (2018). Mitigation of Hot-Spots in Photovoltaic Systems Using Distributed Power Electronics. *Energies 2018, Vol. 11, Page 726*, *11*(4), 726. https://doi.org/10.3390/EN11040726

Olivier, J. G. J., & Peters, J. A. H. W. (2020). *TRENDS IN GLOBAL CO 2 AND TOTAL GREENHOUSE GAS EMISSIONS 2019 Report*.

Pandian, A., Bansal, K., Thiruvadigal, D. J., & Sakthivel, S. (2016). Fire Hazards and Overheating Caused by Shading Faults on Photo Voltaic Solar Panel. *Fire Technology*, *52*(2), 349–364. https://doi.org/10.1007/S10694-015-0509-7/FIGURES/7

Ramaraj, R., Pounraj, P., Prince Winston, D., Sakthi Suriya Raj, J. S., & Cynthia Christabel, S. (2015). Analysis of PV power generation under partial shading and hotspot condition. *International Journal of Applied Engineering Research*, *10*(55), 3443–3447.

Rijksoverheid. (2022). *Windenergie op zee | Duurzame energie | Rijksoverheid.nl*. https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee

TNO. (2022). *Potential for significant savings on solar farm costs*. https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/renewable-electricity/solar-energy/solar-farm/solar-farm-cost/

Vieira, R. G., de Araújo, F. M. U., Dhimish, M., & Guerra, M. I. S. (2020). A comprehensive review on bypass diode application on photovoltaic modules. *Energies*, *13*(10), 1–21. https://doi.org/10.3390/en13102472

Williams, M. E. (2014). Repair of deteriorated bridge substructures using carbon fiber-reinforced polymer (CFRP) composites. *Advanced Composites in Bridge Construction and Repair*, 265–286. https://doi.org/10.1533/9780857097019.2.265