UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

INVESTIGATION OF FACTORS AFFECTING THE OPERATION OF SILICON CRYSTAL SOLAR CELLS AND THEIR CONDITION ASSESSMENT METHODOLOGY

Booklet of PhD Theses

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1. INTRODUCTION AND OBJECTIVES

It is a known fact for a long time that solar energy is the energy source with the greatest potential, which could satisfy many times the entire energy demand of the Earth. In addition to being an abundantly available, clean and renewable source of energy, it is accordingly suitable for meeting the currently valid climate goals. The trends measured during the last decades clearly show the direction that humanity has sought to exploit the solar energy arriving on our planet as efficiently as possible and to an ever greater extent.

European countries have always been at the forefront of exploiting renewable energy sources, and in recent years Hungary has also joined the European forefront in terms of solar power plant capacity. At the same time, the extremely populous and dynamically developing Far Eastern countries have a huge energy hunger, which should be covered from as many sources as possible, even with solar energy. Furthermore, several of the currently most polluting countries are located in this region, so the solar power plant potential in Asia is understandably growing exponentially. In China alone, solar capacity has been expanded by several tens of gigawatts annually in recent years. For many years, this expansion value was equivalent to the entire German capacity that had already been built.

It is important to emphasize that in the case of solar energy, we are talking about an energy source in which the population has a serious role to play in exploiting it as widely as possible, alongside the political forces and economic giants that govern the countries. Household-sized small power plants (HMKE) make a significant contribution to the utilization of solar energy worldwide. Domestic HMKE production dominated Hungarian solar energy production for years, and today it accounts for nearly a third of the total capacity. However, HMKE does not necessarily appear only on the production side of the electricity system, but also triggers a demand for consumption at the point of use. This reduces the energy demand on the national grid, and at the same time, the public grid also solves "energy storage" in the case of systems that feed into the grid, that is, it has solved it. During the last few months, however, the electricity and energy sector has called for an important, strategic change. The biggest concern of the domestic system, and at the same time the electricity system of every other country, is energy storage.

It should be pointed out that the increasingly widespread exploitation of solar energy also exacerbates the problems of the lack of energy storage. Hungary does not have the geographical features to remedy the problem by building large-capacity pumped-reservoir power plants. Battery energy storage, which functions as a quick solution, is expected to spread in the near future. Furthermore, Figure 1 supports the general opinion that it is not expected that renewable energy sources will completely displace traditional energy sources in the coming decades, this is also true for Hungary.

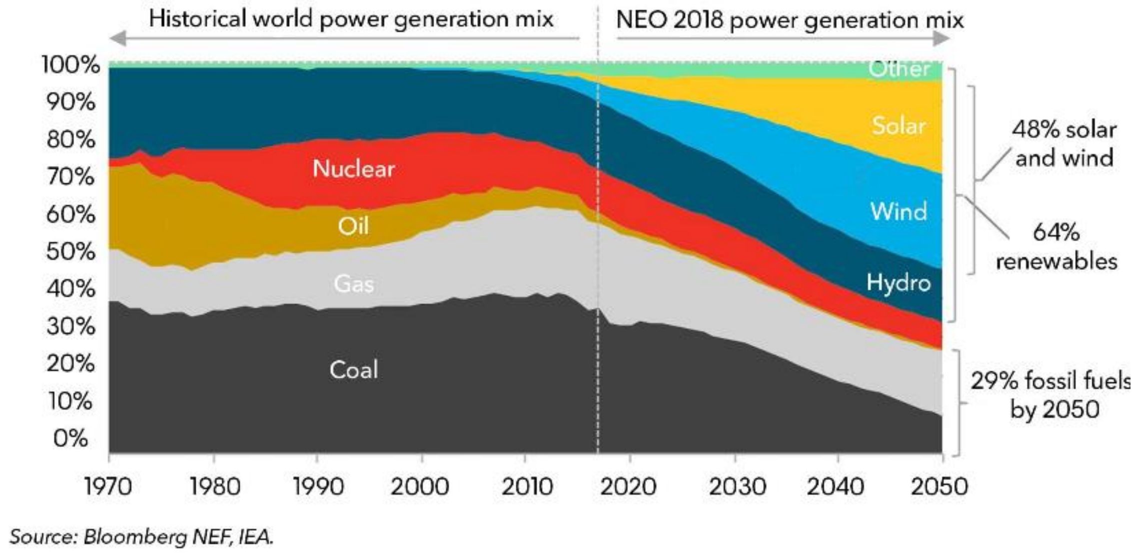


Figure 1. *The percentage share of different energy sources in the world's electricity production.*

There is no doubt that in the case of solar energy production, most of the criticism is directed at the efficiency of energy conversion, although this parameter has also been able to improve in recent years. The efficiency of solar modules is influenced by many factors, from production to installation to the duration of operation. Regardless of the maximum efficiency of the production technology and the purity of the materials used, external factors (e.g. dirty surface, load level, high temperature) can reduce the electrical performance of photovoltaic panels [1]. The effect of many of these factors can be reduced or even completely eliminated.

Kazem et al. [2] report that a solar system can lose more than 10% of the energy produced if it is not cleaned monthly. Because surface contamination can primarily cause a drop in current and indirectly a drop in voltage [3]. Depending on the geographical features, this loss can reach up to 17% [4, 5]. If Hungary primarily focuses on the exploitation of solar energy, the maximum efficiency of the existing and planned power plants must be ensured in addition to the development of energy storage options.

In my dissertation, I present the current role of solar power plants in the Hungarian electricity system. This is followed by a brief overview of the theoretical operation of solar cells. I monitored the practical operation during laboratory and outdoor tests, during which I examined the aforementioned factors that have a negative influence on efficiency. Among other things, my goal is to outline the most common sources of surface contamination and to examine their effects [6–8]. These chapters create the basis for the presentation of the condition assessment of solar power plants - the testing methodology, fault finding and fault identification. My goal is to eliminate the false belief that solar power plants are undemanding, maintenance-free power plants, or from an economic point of view, investments, investments.

My dissertation represents something new in its practical significance, emphasizing that, unlike the usual norms, more attention should be paid to performance degradation and lifespan reduction, so not only economic aspects matter.

2. INVESTIGATED MATERIALS AND TECHNOLOGIES

2.1. INVESTIGATION OF THE EFFECTS OF POLLUTANTS

Manufacturers and distributors typically characterize their products with peak performance. However, this peak value is rarely reached by the solar cell, as it depends on many factors, such as the degree of illumination, the angle of incidence of the sun's rays or some shading effect. Dirt on the surface of the solar panel also has a shading effect. Research into the effects of pollution has been going on for some time in the solar laboratory of our department.

During the previous measurements, the spreading was usually done with a spoon of some kind. My assumption was that the influencing effect of the method of application on the electrotechnical parameters of the solar cell can be verified with measurements. In addition to the spoon, I used the sieve as a new spreading tool, and compared the differences that can be read from the measurement data by the two tools.

Expected consequences justifying the need for shifting trough sieve:

- the pollutant is better distributed on the surface,
- more closely approximates the real deposition,
- eliminates differences in large particle sizes (selecting larger grains),
- a greater reduction in performance will be experienced, which will make it difficult to supply a possible consumer safely.

2.1.1. PROCEDURE OF THE MEASUREMENTS

The measurements were carried out in the solar laboratory of the Institute of Electrical Engineering and Electronics. I placed the Korax Solar 80 Wp monocrystalline solar panel on a table, above which I attached a "solar simulator" consisting of 8 reflectors [9, 10, 11, 12]. The solar cell was illuminated by 1000 W halogen bulbs, however, the illumination is not uniform due to the space between the reflectors (*Figure 2*). The median value of illumination was 874 W/m^2 [12, 13]. Parameters characteristic of the solar panel: P_{max}: 85 W, A_{useful}: 1.5 m^2. Measured electrical parameters: the no-load voltage of the solar cell and the short-circuit current. The constant of the spectral composition of light is 0.532, which is the ratio of the areas under the curve determined by the spectrophotometer. [2, 9, 14]. This means that the measured current with a halogen reflector solar simulator compared to sunlight is 53.2% of the real value. These electrical parameters were measured with a METRIX MX-59HD digital multimeter. I repeated the spreading of the pollutants with three different tools, two sieves with different hole diameters and a kitchen plastic spoon. I measured the pollutant doses with a Voltcraft PS-200B jewelry scale.

Figure 2. *The solar panel illuminated by the solar simulator.*

I started all measurements when a no-load voltage value of 17.5 V was reached. During the experiments, I increased the amount of the pollutant in increments of 5 g up to 75 g. I was able to measure the powder doses very precisely with the scale mentioned in the previous chapter. I examined four materials, farmland, sand, ash and city dust, as well as three tools, two sieves with different hole diameters and a spoon (Table 1). I pre-sifted the fractions of different particle sizes, so that all the material could fall on the surface when applied to the surface of the solar panel after measurement.

Before the tests, the temperature transient phenomenon, when the electrical parameters change rapidly, took place during the warm-up process. After 20 minutes, the surface temperature of the panel rose from 23 C° to over 70 C°, at which point the voltage settled to a constant value. In all cases, the contamination of the surface with dust began after the temperature transient phenomenon ended [9].

Table 1. *The relationship between the strewing tools and pollutants used during the tests.*

	1. tool	**2. tool**	**3. tool**
Name	E1	E2	E3
Marking on diagram	triangle	square	circle
Tool type	spoon	sieve	sieve
The diameter of the sieve hole	-	0,9 mm	0,5 mm
Particle size of dispersed pollutant	soil: 0,1 – 6 mm sand: 0,3 – 3 mm	Particles smaller than 0.9 mm but larger than 0.5 mm	Particles smaller than 0.5 mm

2.1.2. UNLOADED SOLAR PANEL CONTAMINATION TEST

Three of the four materials used do not require a serious description, but the definition of the fourth is unavoidable. We gave the material the name city dust, as it was collected from a garage. The explanation for this is that the dust falling from the car in the garage is a mixture of many different substances. It may contain soil, oil residues from cars, tire wear and all other pollutants that may be present in the urban environment and traffic. The purpose of using the material was that similar drifting dust may be present in the air in an urban environment, which may form a deposit on any solar panel.

Since it was possible to set the exact doses of pollutants by mass measurement, density as a physical parameter played a significant role. For example, the difference in density between ash and sand is almost three times, so ash, with a much lower concentration compared to sand, could cover a much larger surface on the solar panel (*Table 2*).

Table 2. *Physical characteristics of the various materials used.*

Pollutant	**Colour (on diagram)**	**Density [g/cm^3]**	**Specific Surface Area [mm^2/g]**	**Grain Size [mm]**
sand	blue	1,45	~0,30	0,2…0,8
ash	brown	0,6	~0,66	0,1…1,4
soil	red	0,8	~0,35	0,1…6
urban powder	green	n/a	n/a	< 0,5

2.1.3. VOLTAGE DROP AS A FUNCTION OF CONCENTRATION

Since it was necessary to condense the results of several measurement series into one figure (*Figure 3*), I marked the material types with colors: farmland is red, ash is brown, sand is blue, and city dust is green. Furthermore, I differentiated the intervals used (E1, E2 and E3) by varying the markers of the series (triangle, square and circle).

In the case of ash pollution, a maximum voltage drop of 10% was experienced with the use of a spoon and a concentration of 75 g/panel. The most significant reducing effect of urban dust and soil pollutants was 7.8%, while sand was 3%. The significant lag of sand in pollution can be explained by the fact that sand has a brighter surface and reflects more light. As a result, the heat-absorbing capacity is smaller, and a smaller decrease is also observed in the case of the voltage values.

Similar to the other application methods, a maximum voltage drop of 19% was experienced in the case of the ash pollutant with the use of a sieve producing a larger particle size fraction and a concentration of 75 g/panel. The most significant reducing effect of earth was 8.5%, whereas this value was 7% in the case of sand.

A maximum voltage drop of 24% was experienced in the case of the ash pollutant with the finest particle size and 75 g/panel concentration. The most significant reducing effect of urban dust was 14%, whereas this value was 10% for earth and 8% for sand. The result obtained with urban dust is less far behind the value observed in the case of sand and earth, however, the reduction measured in the case of ash was still extremely high compared to the other three materials, which can be attributed to the density of the different materials. The order and pattern of the trend lines developed similarly for all application methods. Similar results were reported by Abderrezek et al. [6], Bhattacharya et al. [10], Sadat et al. [15], and Oh et al. [16].

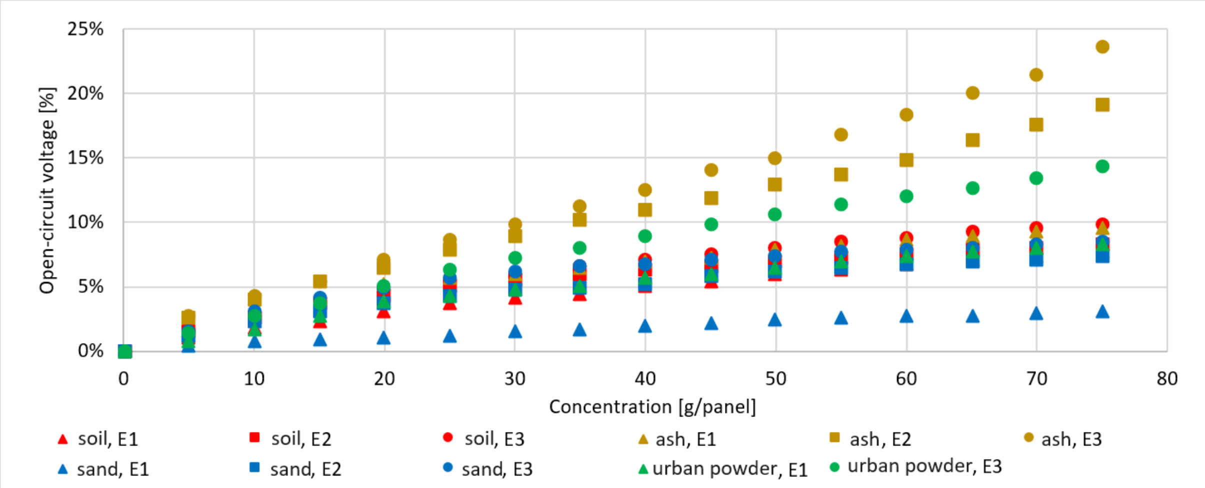


Figure 3. *Open-circuit voltage reduction effect of surface contamination.*

2.1.4. Current reduction depending on concentration

In the case of a decrease in current strength, the data series are better separated according to the pollutants used (*Figure 4*). In the case of the ash contaminant, a maximum current reduction of 84% was observed with the use of a spoon and a concentration of 75 g/panel. The most significant reducing effect of the urban dust pollutant was 58%, whereas in the case of earth and sand it was 27% and 14%, respectively. Similar to the other application methods, a maximum current reduction of 91% was observed for the ash pollutant with the use of a sieve producing a larger particle size fraction and a concentration of 75 g/panel. The most significant reducing effect of earth was 44%, whereas this value was 21% for sand. In the case of the ash contaminant, a maximum current reduction of 95% was experienced at the finest particle size and 75 g/panel concentration. The most significant reducing effect of urban dust was 77%, whereas this value was 53% for earth and 30% for sand. The explanation for this can again be traced back to the grain size, as well as the density difference between the materials and the typical grain size. The order and pattern of the trend lines developed similarly for all application methods.

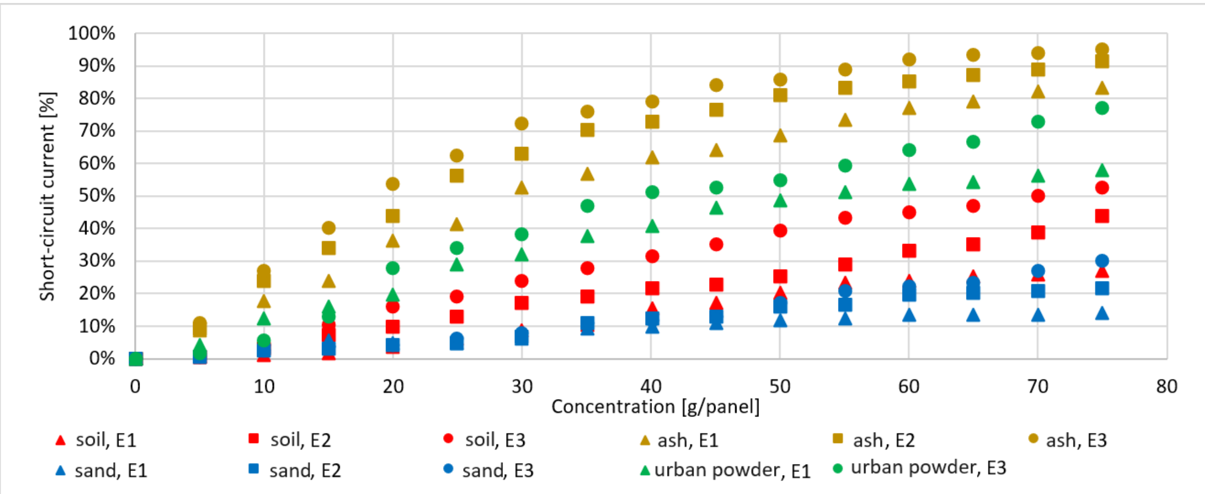
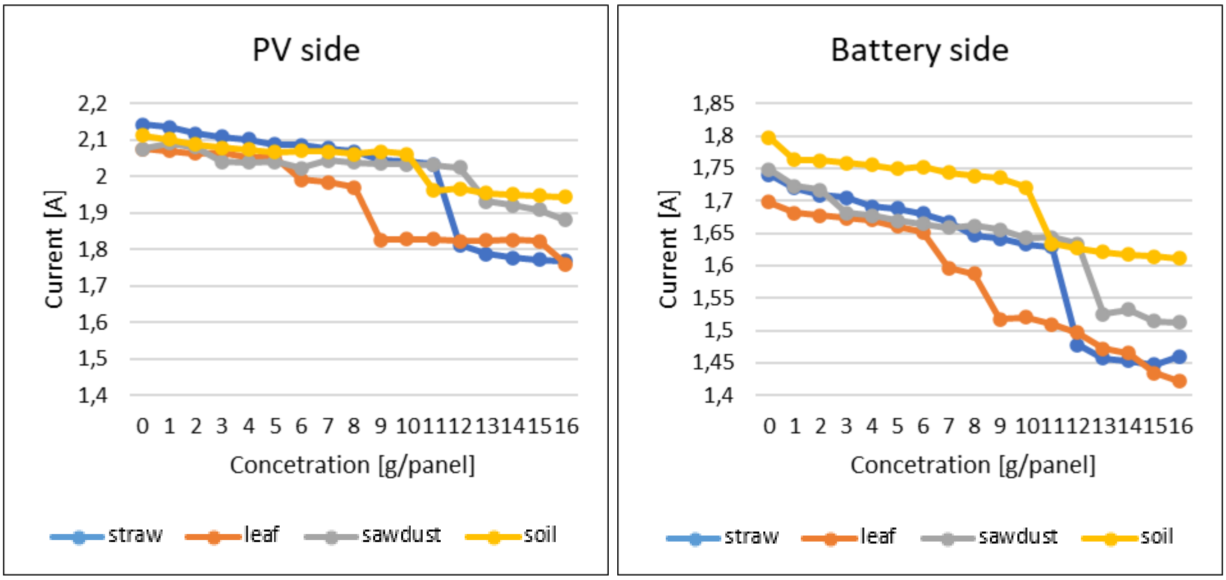


Figure 4. *Short-circuit current-reducing effect of surface contamination.*

2.1.5. Investigation of loaded solar panel contamination with organic meterials

I made measurements with the same 80 Wp monocrystalline solar cell, but connected the solar cell to an MPPT charge controller and set it to charge a battery. I increased the concentration of the pollutant to the level of 16 g/panel, since the density of ground organic pollutants is extremely low. The essence of the loaded solar cell test is that the operation of the MPPT can be observed. On the graphs, you can clearly see the breaks that indicate the intervention of the work point monitoring regulatory circuit. At that time, the contamination of the surface meant reaching a critical limit value in the reduction of the current, when it was necessary to choose a new working point (*Figure 5 (a)*). I measured both the change in the current supplied by the solar cell and the charging current (*Figure 5 (b)*). By definition, this also meant a drastic loss of performance.

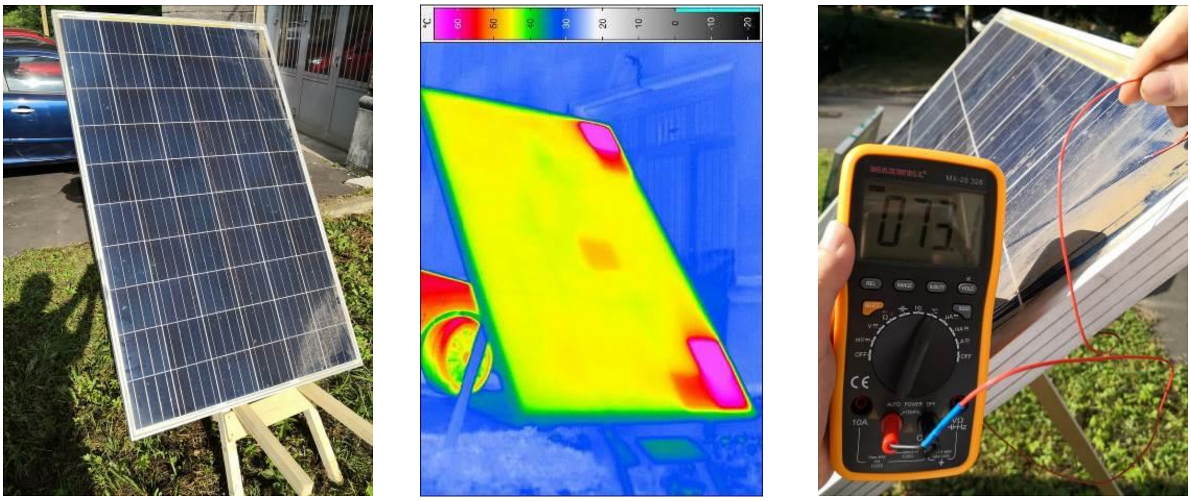


a b

***Figure 5.** The effect of surface contamination reducing the current.*

2.2. Thermal camera investigation of surface contamination and shadow effects

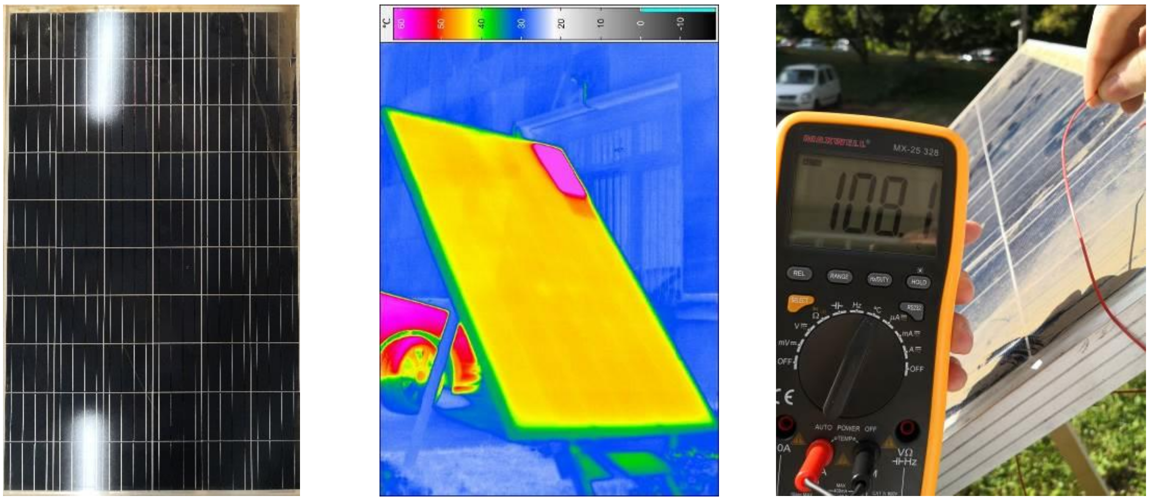
The recordings shown in Figure 6 were not taken during a power plant survey, but during a reference experiment carried out at the University of Miskolc. The tested 260 Wp solar modules come from a power plant, but they have been decommissioned. In *Figure 6 (a)* (the normal, visual image of the module), it can be observed that surface contamination has been deposited in the upper and lower right corners. The panel was short-circuited facing the sunlight. It has already reached its average operating temperature of 45 °C within 20 minutes from the indoor room temperature (21°C). However, significant overheating was experienced in the two corners due to contamination. Hot-spot phenomena can be seen in thermal *image 6 (b)*, which was taken using a Jenpotik Variocam. The maximum temperature exceeded 73°C *(Figure 6 (c))*, which was verified by contact thermometry [17, 18, 19].



(a) (b) (c)

Figure 6. *(a) visual, (b) thermal image of a panel contaminated at two corner points, and (c) checking the temperature of the hot spot with a contact thermometer.*

Figure 7 shows the result of a similar process. In this case, the experiment was carried out on another panel (but of the same manufacture) with only the top corner contaminated (*Figure 7(a)*). Since this panel with almost the same performance produced only one hot spot (*Figure 7 (b)*), it had to withstand higher heat development. In this case, the hot spot was more than double the average panel temperature, exceeding the temperature of 108 °C (*Figure 7 (c)*).

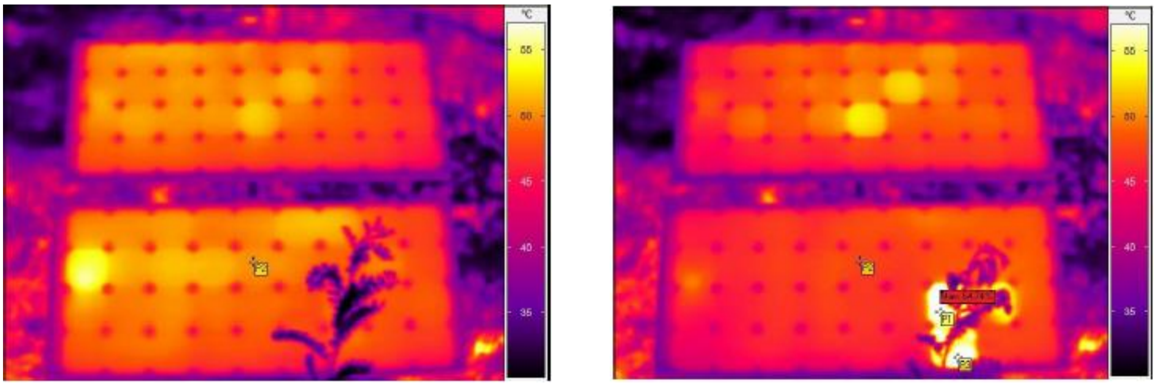


(a) (b) (c)

Figure 7. *(a) visual, (b) thermal image of a panel contaminated at a corner point, and (c) checking the temperature of the hot spot with a contact thermometer.*

Carrying out reference measurements for investigating the effect of vegetation is a simple task. In the first case, two 80 Wp peak power modules were placed on a rack. The modules were not connected and were shorted individually. The operation of the upper module was not affected, but the lower module was subjected to a shadow effect test (*Figures 8 and 9*).

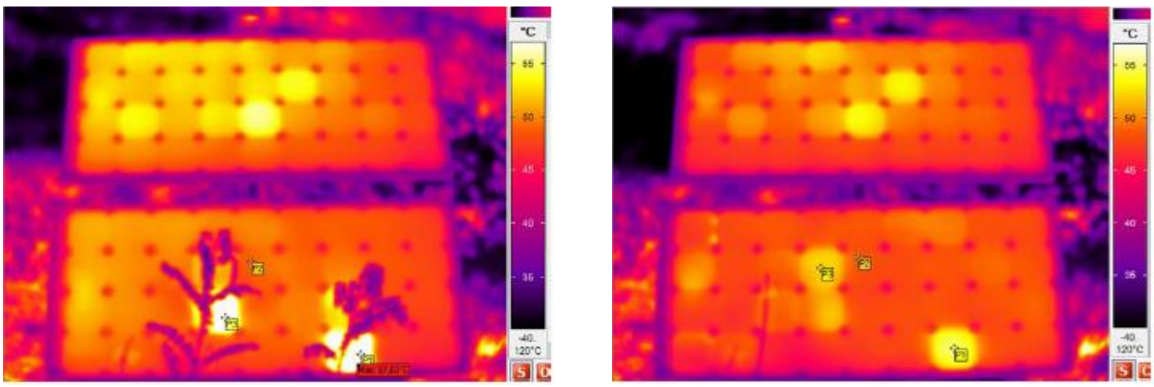
Figure 8 (a) shows the initial state of the experiment, when the temperature of all cells is still almost the same (50 °C), but a shadow effect appears. The temperature of the hotspot caused by the vegetation is 64 °C, the phenomenon also affects 3 neighboring cells (*Figure 8 (b)*). On the back of the left edge of the image of the modules is the switch box with the bypass diodes. This 80 Wp module is divided into two cell strings. The upper two rows and the lower two rows can be isolated separately with diodes. As a result of the shadow phenomenon, the current of the lower module was reduced by half, thereby also its performance [17, 20].



(a) (b)

Figure 8. *(a) initial state, (b) hot-spot phenomenon of the investigation of the shade effect of the vegetation.*

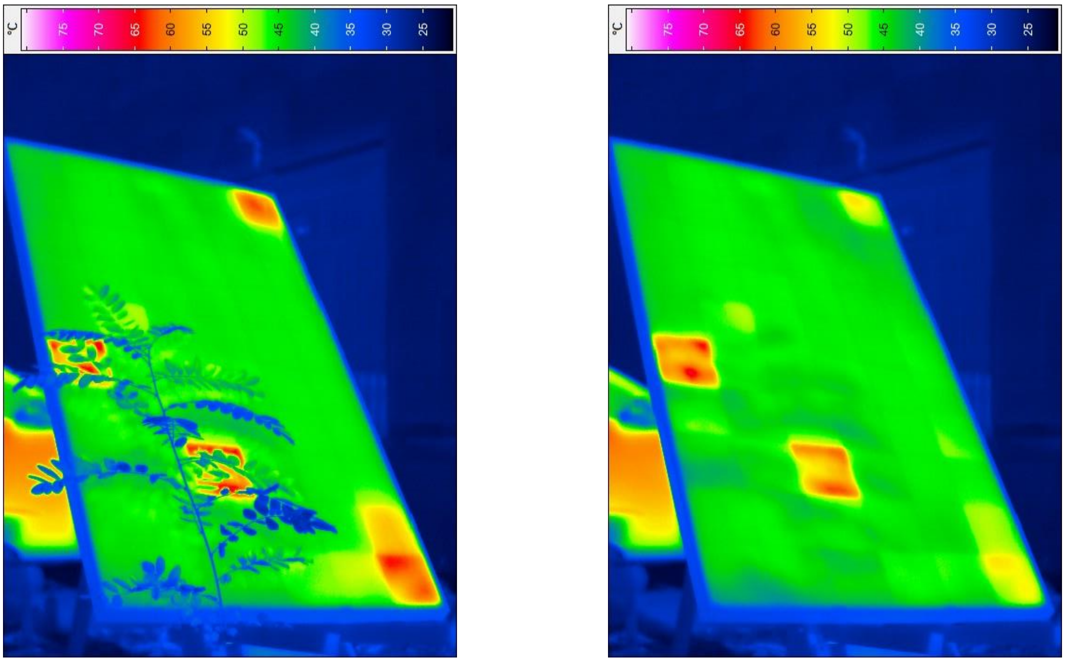
Figure 9 (a) shows the state when another shading plant was placed in front of the module. *Figure 9 (b)* shows the state after the shadow effects have disappeared. Overheating of the cells persists for a long time even after the disturbing effect ceases and can therefore negatively affect energy production.



(a) (b)

Figure 9. *(a) Increasing the shadow effect of the vegetation, (b) state after the shadow effect has ceased.*

I also performed the experiment with a power plant-sized module (*Figure 10*), which is of the same make as the one on which the flash and electroluminescence tests were performed. It should not be overlooked that in the event of a solar panel failure caused by shadow effects, we cannot expect a warranty replacement, because the failure is not the result of a manufacturer's error, but of an operator's error. It is therefore recommended, on the one hand, to reveal the condition of the solar panels and possible shadow phenomena with a thermal camera of suitable sensitivity during installation, and to have them checked on an annual basis. If cell defects are experienced even after installation, even during the first use, it is advisable to contact the distributor/manufacturer immediately, because then the warranty can still be enforced.



(a) (b)

Figure 10. *(a) Shade effect of the power plant module with a tree branch, (b) state after removing the shielding of the power plant module.*

2.3. Large sample flash test evaluation

It is impossible to report data from more than 1000 panels in as much detail as in previous chapters, so a statistical summary is much more expedient. In this summary, we compared the results of the flash test available for each module. Five values are derived from the flash tests: MPP power, MPP voltage, open circuit voltage, MPP current and short circuit current. Also, only one value is based on in-situ measurement at the solar power plant, which is the actual power value.

Figure 11 shows the distribution of two value types, MPP power and actual power. The MPP power values are derived directly from the flash test, whereas the actual power values are the results of the in-situ measurement. A closer look at the distribution of the MPP power series shows that the maximum performance of many panels is around 270 W. This was explained by the fact that, unlike the official data (260 Wp), many modules were already more powerful than the others at the time of installation. According to the results in the third column of Table 1, the modules have a power of 260 Wp and the value of the performance tolerance (3%) and measurement tolerance is 3%. This means that the minimum permissible power value during installation is 252.2 W, which changes to 244.63 W with the measuring tolerance. On the other hand, the maximum power is 267.8 W, with the measuring tolerance this value is 275.83 W.

The median of MPP power series is 259.70 Wp, and the average MPP power value is 250.76 Wp. The average difference is 17.68 Wp and the standard deviation is 36.98 Wp. 29% of the values is between of 250 W and 260 W (313 modules). Around 27% of MPP power values are less than 252.2 W (282 modules) and 16% is less than 244.63 W (173 modules). The panels have a 90% performance guarantee for the first 10 years and an 85% performance guarantee for the next 10-25 years. After four years, 10% of the modules (107 modules) suffered a performance reduction of more than 10%. If the actual power values are taken into account, we get a much worse end result after summing the data. The median of actual power series is 221.55 Wp, and the average actual power value is 215.68 Wp. The average difference of actual power series is 19.27 Wp and the standard deviation is 34.49 Wp. 3% of the values is between of 250 W and 260 W (313 modules). Around 98% of MPP power values are less than 252.2 W (1043 modules) and 92% is less than 244.63 W (976 modules). Furthermore, 76% of the modules (811 modules) suffered a performance reduction of more than 10%.

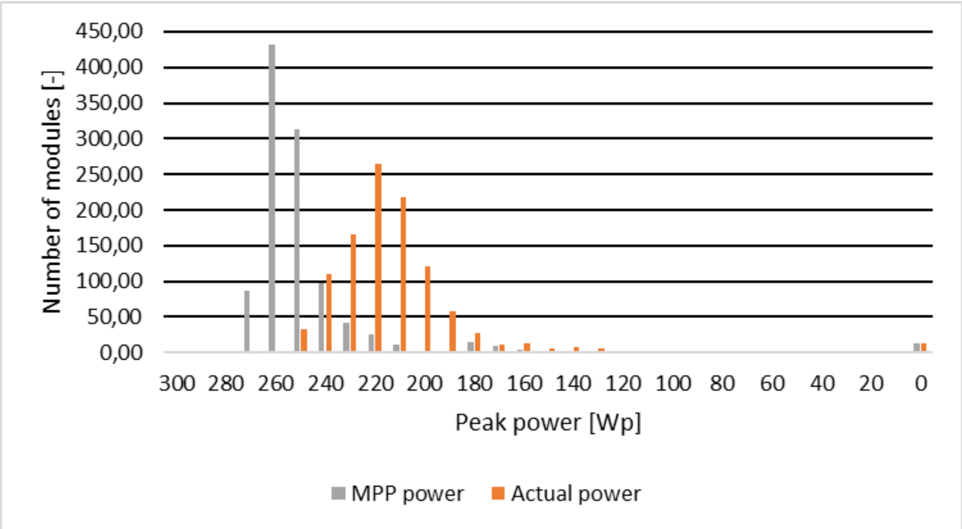


Figure 11. *Distribution of measured power values.*

Figure 12 shows the distribution of measured voltage series. The median of MPP voltage series is 34.44 V, and the average MPP voltage value is 33.56 V. The average difference of MPP voltage series is 1.78 V and the standard deviation is 4.34 V. 45% of the values is between of 34 V and 35 V (476 modules) and 51% of the values is under 34.4 V (manufacturer data from Table 1). The median of open circuit voltage series is 36.7 V, and the average open circuit voltage value is 36.01 V. The average difference of open circuit voltage series is 1.43 V and the standard deviation is 4.30 V. 55% of the values is between of 36 V and 37 V (583 modules) and 61% of the values is under 36.54 V (manufacturer data from Table 1).

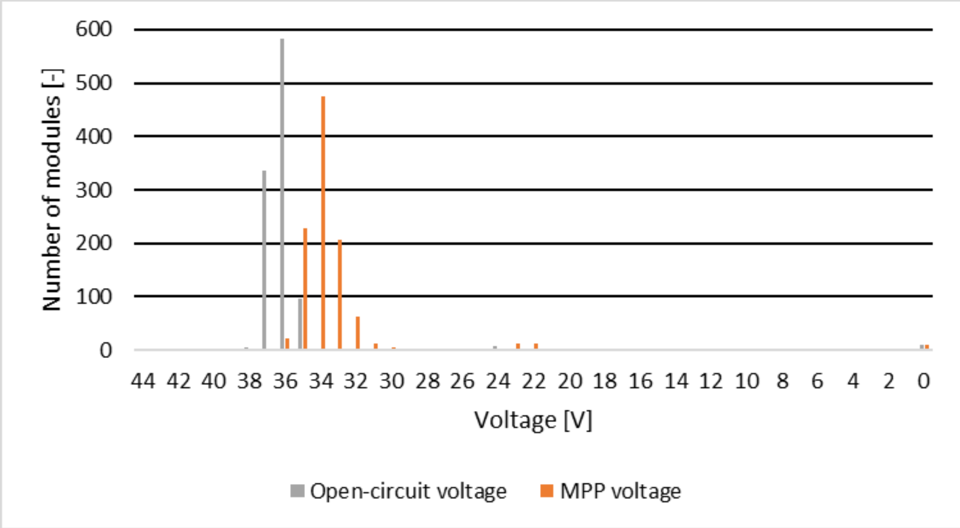


Figure 12. *Distribution of measured voltage values.*

Figure 13 shows the distribution of measured current series. The median of MPP current series is 7.53 A, and the average MPP current value is 7.38 A. The average difference of MPP current series is 0.34 A and the standard deviation is 0.93 A. 56% of the values is between of 7.5 A and 8.0 A (594 modules) and 37% of the values is under 7.47 A (manufacturer data from Table 1). The median of short circuit current series is 8.24 A, and the average short circuit current value is 8.13 A. The average difference of short circuit current series is 0.33 A and the standard deviation is 0.97 A. 66% of the values is between of 8.0 A and 8.5 A (699 modules) and 11% of the values is under 7.92 A (manufacturer data from Table 1).

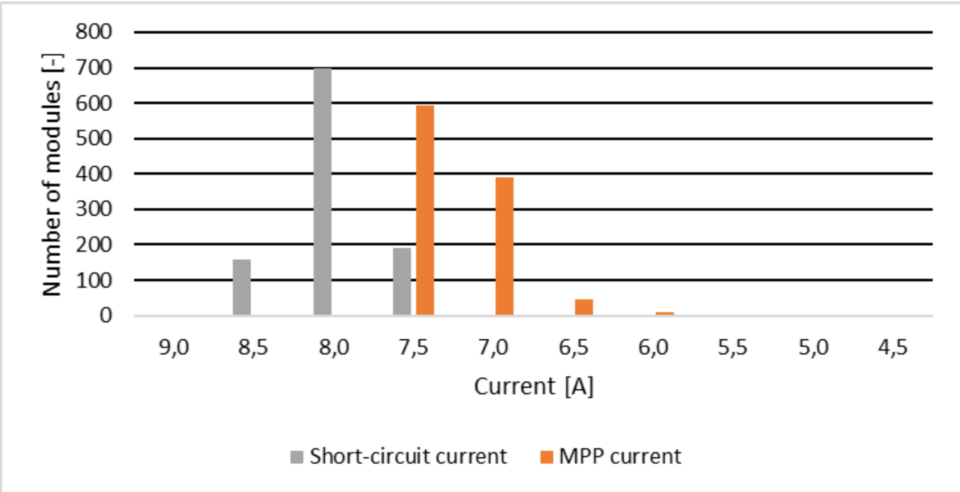


Figure 13. *Distribution of measured current values.*

2.4. Replacement of EL camera with thermal camera

I would like to prove that thermography and electroluminescence images are compatible with each other. The basis of the similarity is Joule heat. As I described earlier, the resistance of the damaged cell parts changes, so they generate more heat. Since the differences are visible in the EL images, a similar result should also be achieved during the thermographic examination [21, 22]. I started the research work on the smaller and larger power panels of the departmental laboratory. In the 10 Wp performance category, I tested both monocrystalline and polycrystalline panels. The differences are clearly visible in the thermographic images, the heat distribution pattern of the panels is different. The differences can best be stopped in the ninth minute (*Figure 14 (a4), (b4), (c4)*). From this, I came to the conclusion that there may be different types of cell damage on the examined panels. Furthermore, it has been proven that the thermographic examination is an effective method. However, no EL images have been taken of the panels yet.

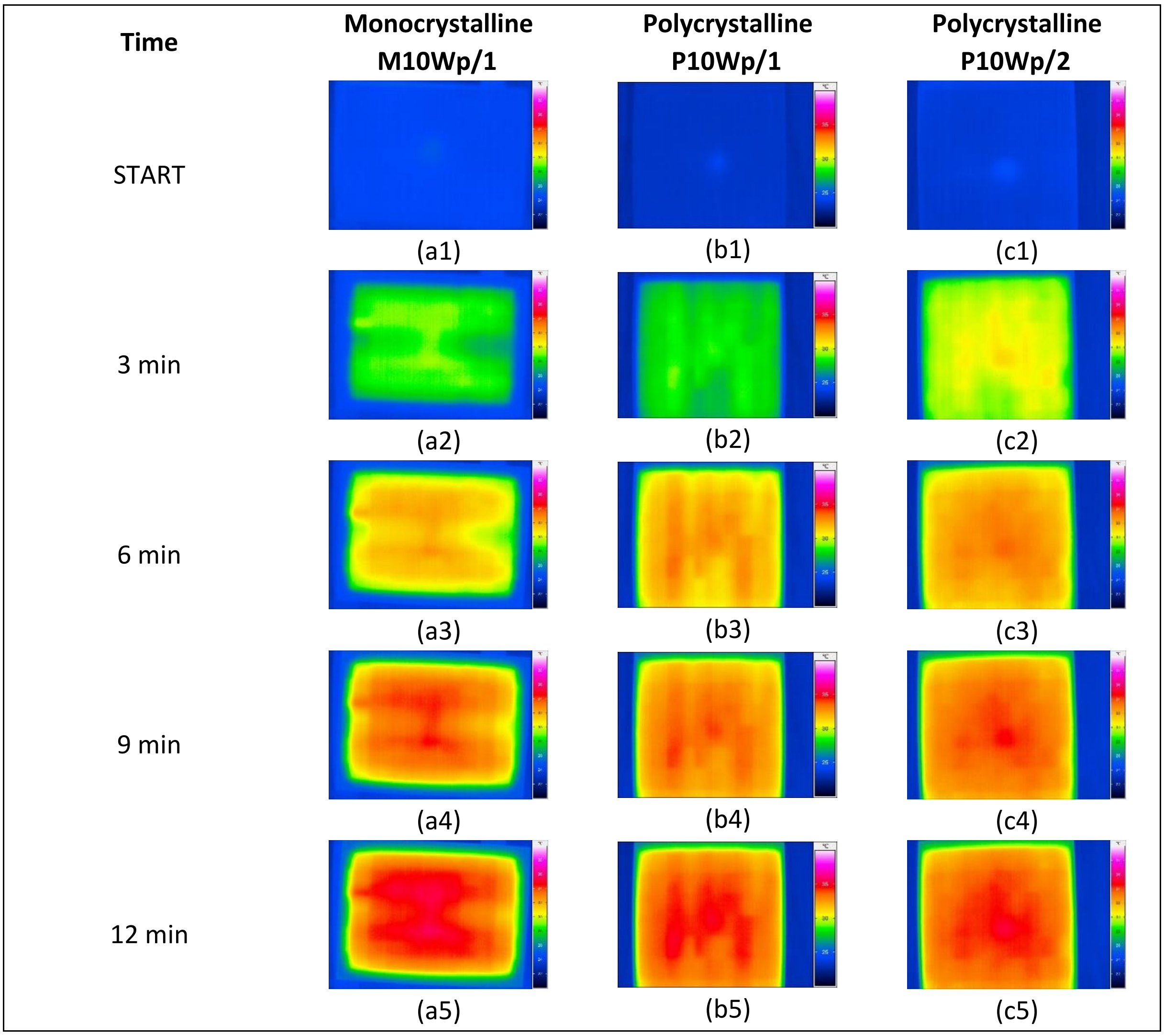


Figure 14. *Thermal camera image of 10 Wp solar panels.*

Currently, I could only test polycrystalline panels in the 20 Wp performance category. All three samples come from the same manufacturer. The differences between the final result and the panels are not as spectacular as with the 10 Wp panels. However, minor differences can be detected (*Figure 15*). The P20Wp/2 panel emitted more heat than the other two panels already in the third minute. Based on the pictures, we have come to the conclusion that the panels are in better condition than the 10 Wp ones. No electroluminescence recordings have been made of the panels yet, because currently only one of our industry partners has this technology.

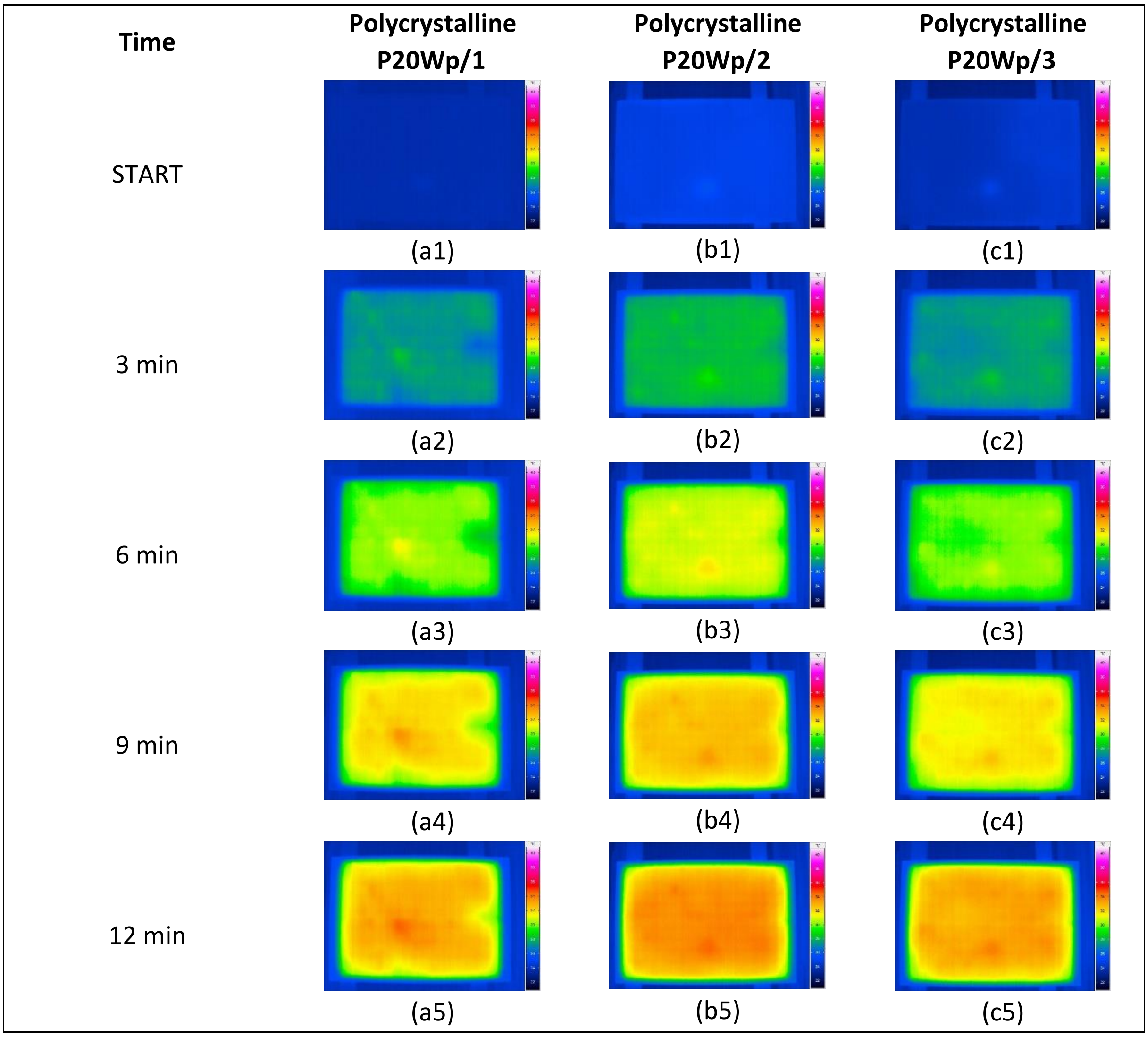


Figure 15. *Thermal camera image of 20 Wp solar panels.*

3. NEW SCIENTIFIC RESULTS – THESES

T1. *The scattering of numerous dust-like pollutants on the surface of the solar cells was repeated with different devices in order to test the various natural deposition patterns as closely as possible, which could not be found in the domestic and international literature. Two types of samples were examined, the spot-like and uniformly dispersed deposition samples on the surface. The obtained results divided the research direction into two, spot-like deposits in the topic of condition assessment, while the uniform deposit image was further applied in the topic of performance testing.*

It was demonstrated that for all contaminant types, the uniformly dispersed pattern produced greater reductions than the spot-like deposition patterns. Also, in the case of uniform spreading, the decrease in the hole diameter of the screen was inversely proportional to the induced power loss. The findings are supported by the measured electrical parameter changes:

a) Depending on the used scattering device and the hole diameter, **the voltage drops** in the case of a surface contamination concentration of 75 g/panel developed as follows:

	ash	***urban powder***	***soil***	***sand***
spot-like deposit	*10%*	*8%*	*7,8%*	*3%*
uniform, *larger hole diameter*	*19%*	*no data*	*8,5%*	*7%*
uniform, *smaller hole diameter*	*24%*	*14%*	*10%*	*8%*

b) Depending on the used scattering device and the hole diameter, **the current decrease** in the case of a surface contamination concentration of 75 g/panel developed as follows:

	ash	***urban powder***	***soil***	***sand***
spot-like deposit	*84%*	*58%*	*27%*	*14%*
uniform, *larger hole diameter*	*91%*	*no data*	*44%*	*21%*
uniform, *smaller hole diameter*	*95%*	*77%*	*53%*	*30%*

The research results clearly support that spot-like dirt patterns have a 50-70% smaller effect on the voltage of the solar panels and a 10-50% smaller effect on the current than evenly deposited dirt patterns. As a result, only the uniform deposition pattern was used in the research investigating further performance reduction. **The spot-like deposits form a thick, point-like thermal insulation layer on the surface of the panel and render the covered solar cells completely inactive.** These effects can be further investigated in the context of the condition assessment.

<u>Own publications related to the T1 thesis:</u> [S8], [S13]

T2. *Their effect on the operation of the solar panel depends on the physical and chemical properties of the impurities deposited on the surface of the solar panel. Considering the literature, it is unique that organic substances were also investigated, as pollutants that are often deposited on the surface. The previous T1. based on the findings of the thesis, the pollutants were evenly dispersed on the surface, and I used the same Korax Solar 80 Wp solar panel.*

The current that was searched for and identified by the pollution investigation was the intervention of the charge control circuit connected to the solar panel.

It was established that the pollutant concentrations linked to the intervention of the charging control circuit are the following in order:

	leaves	soil	straw	sawdust
	8 g/panel	*10 g/panel*	*11 g/panel*	*12 g/panel*
or	*16 g/m^2*	*20 g/m^2*	*22 g/m^2*	*24 g/m^2*

It has been proven that when a pollutant concentration of 16-24 g/m2, which is lower than the level (60-80g/m2) experienced during the condition assessment of solar power plants, the intervention of the control electronics was already necessary, in order to maintain the work point with the maximum available power. Based on the results, it was confirmed that these regulations represent an 8-12% jump in the amount of electricity supplied and this results in a direct network reaction.

Own publications related to the T2 thesis: [S2], [S8], [S13]

T3. *The methodology of thermographic fault finding is subject to many criticisms, which cast doubt on its authenticity. It is a fact that during the condition assessment, several recommendations guaranteeing the correctness of the final result must be followed, such as the choice of the camera's viewing angle and its calculated distance from the panels. During the review of the literature, I found that the studies are typically more reports, in which they primarily only present different thermal images, and are less concerned with their formation or occurrence.*

On the other hand, during the research work, it was proven that it is possible to create artificially, under controlled conditions, conditions that result in a heat-generating effect for various reasons, such as surface contamination, or the natural and artificial shadow effect, as well as internal fractures inherent in light-sensitive material. and cracks. Conditions similar to the previous ones can also be registered during actual power plant condition surveys. **Based on the test results, it can be stated that a temperature difference of less than 15 °C can still occur in the case of intact panels, however, spots and point-like dirt samples deposited on the surface, or the shadow effect of vegetation can cause differences of up to 30-60 °C. Such large-scale thermal effects cause irreversible damage to the semiconductor material, which causes rapid degradation and a reduction in expected service life.** At the same time, the inspection with a thermal camera alone is not sufficient for accurate fault identification, a comprehensive picture of the state of a solar power plant can be obtained by combining several tests.

Own publications related to the T3 thesis: [S5], [S6], [S11]

T4. *It is unique in the field of the flash test to present results based on the large number of samples presented. Such a survey of more than a thousand samples can answer many questions when understanding the operational problems of a solar power plant. In the years following the installation of the tested solar power plant, the operator noticed a constant loss of production of 10-12% annually.*

a) The condition assessment of the solar power plant in Hungary, which has been operating for four years, clearly confirms that the increased air pollution during the preparation of the fuel of the biomass power plant adjacent to the solar power plant increased the number of failures between the solar panels close to it, due to cell burnouts and failures caused by surface contamination. It can be concluded that the maximum power working point of the damaged solar cells decreased because the V-I characteristic of the tested panels changed due to the damage.

b) Furthermore, it can be established that the various fault phenomena distort the V-I characteristic in a different way compared to that of flawlessly functioning solar cells. After analysing the images provided by the electroluminescence test, it can be stated that the number and arrangement of defects appearing in the semiconductor silicon material is related to the distortion of the characteristic.

Own publications related to the T4 thesis: [S3], [S5], [S6], [S11]

T5. *Examination of the relationship between thermography and electroluminescence performed with a thermal camera is an absolute gap-filler. The current passing through the solar panels connected to the electric power supply not only causes the emission of photons close to the infrared range, but also causes heating in the damaged, cracked or fragmented silicon-based light-sensitive material.*

In the case of the different panels, different thermal profiles and completely unique patterns have developed. The results clearly support that the panels were damaged at different points. During electroluminescence, only the location of the defects can be seen, and their type can be determined with high accuracy, but the amount of heat generated by the defects cannot be deduced only by thermographic examination.

It has been proven that the connection and comparison of the two test methods is of great help in the in-depth study and understanding of hot-spot phenomena.

Finally, it should be noted that the combined application of the three test methods (thermography, flash, electroluminescence) can give a comprehensive picture of the condition and degree of damage of the solar cells.

Own publications related to the T5 thesis: [S4], [S5], [S6], [S12]

4. PATHS FOR FURTHER DEVELOPMENT

During the writing of my dissertation, I managed to present and support the opinion that the operation of solar power plants should not be taken lightly. Because it is an energy-generating device that is very prone to breakdowns. It was not my intention to speak against the use of solar energy. I support the transition of our society towards renewable energies, however, like everything, this topic must be approached carefully and consciously, in order to ensure the best possible efficiency.

I examined the temperature dependence of solar cells, as well as the loss of performance caused by impurities. During the presentation of the temperature transient phenomenon, I tried to support the basic theoretical assumptions. I should also draw attention to the possibility of cooling, as well as introduce overheating as a possible source of error.

I also used different pollutants, as well as their different particle sizes, as well as their concentration distributed on the useful surface of the solar cell. Surface contamination has another, more serious consequence, which appears in the form of hot spots and can be investigated with heat mapping.

Among the testing methodologies that can be used during the condition assessment of solar power plants, I presented the thermographic fault finding with a thermal camera, the flash test for determining the electrical parameters and, last but not least, the electroluminescence test, which is suitable for identifying the fault and provides a specific condition test.

I emphasized that electroluminescence can be replaced or supplemented by thermography. In addition to the fact that the solar cell can emit photons, it also emits heat rays, so defective or damaged parts generate more heat due to their increased resistance.

My future goal for continuing the research work is that most scientific sources admit that there are still uncertainties in the evaluation of spots and fractures visible in the recordings, primarily in the identification of electroluminescent defects. The analysis of the recordings can be taught to different algorithms and a large amount of data can be analyzed with greater accuracy and faster in software.

In the future, I plan to continue the processes of the destruction of the light-sensitive silicon crystal layer. I assume that you can speed it up with broken stress tests, while continuously documenting the changes. Both thermographic and electroluminescent cameras can be used during documentation.

5. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

***Quality publications related to the dissertation**:*

[S1] D. Matusz-Kalász, I. Bodnár, R.R. Boros, *Monitoring of MPPT regulation during temperature transient phenomenon in off-grid solar system,* 2023 24nd International Carpathian Control Conference (ICCC), pp. 269-272, 2023, **(SCOPUS indexált)**

[S2] I. Bodnár, D. Matusz-Kalász, R.R. Boros, *Exploration of Solar Panel Damage and Service Life Reduction Using Condition Assessment, Dust Accumulation, and Material Testing,* Sustainability, vol. 15, no. 12, 9615, 2023, **(SCOPUS, Q2, IF: 3.9)**

[S3] G. Kozsely, I. Bodnar, D. Matusz-Kalász, R. Lipták: *Determination of Solar Panel's Characteristics by Flash Testing,* 2022 23nd International Carpathian Control Conference (ICCC), pp. 233-238, 2022, **(SCOPUS indexált)**

[S4] D. Matusz-Kalász, I. Bodnár, *Monitoring and Diagnostics of Photovoltaic Cells by Electroluminescence,* 2022 23nd International Carpathian Control Conference (ICCC), pp. 158-161, 2022, **(SCOPUS)**

[S5] I. Bodnár, D. Matusz-Kalász, R.R. Boros, R. Lipták, *Condition Assessment of Solar Modules by Flash Test and Electroluminescence Test,* Coatings, vol. 11, no. 11, 1361, 2021, **(SCOPUS, Q2, IF: 2.881)**

[S6] I. Bodnár, D. Matusz-Kalász, *Statistical Comparison Between Experimental and Numerical Simulation Results of The Solar Cell,* 2021 22nd International Carpathian Control Conference (ICCC), pp. 1-6, 2021, **(SCOPUS)**

[S7] I. Bodnár, D. Matusz-Kalász, D. Koos, *Experimental and numerical analysis of solar cell temperature transients,* Pollack Periodica. An International Journal for Engineering and Information Sciences, vol. 16. no. 2. pp. 104–109, 2021, **(SCOPUS, Q3)**

[S8] D. Matusz-Kalász, I. Bodnár, *Operation Problems of Solar Panel Caused by the Surface Contamination,* Energies, vol. 14, no. 17, 5461, 2021, **(SCOPUS, Q1, IF: 3.004)**

***Other publications related to the dissertation**:*

[S9] D. Matusz-Kalász, *Hűtött napelemek laboratóriumi és szabadtéri vizsgálata,* Elektrotechnikai és Elektronikai Szeminárium 2022, 2. December, 2022, Miskolc-Egyetemváros, Miskolci Egyetem Gépészmérnöki és Informatikai Kar, Fizikai és Elektrotechnikai Intézet, Elektrotechnikai és Elektronikai Intézeti Tanszék, pp. 98-103.

[S10] D. Matusz-Kalász, *A napenergia szerepe a magyarországi villamosenergiatermelésben,* Acta Academiae Nyiregyhaziensis 7 pp. 99-104, 2022

[S11] D. Matusz-Kalász, P. Balázs, *Napelemek hibáinak feltárása hőkamerás vizsgálattal,* Multidiszciplináris tudományok, vol. 11, no. 3, pp. 112-122, 2021

[S12] D. Matusz-Kalász, R. Lipták, P. Tóth: *Napelemek tönkremenetele,* Multidiszciplináris Tudományok, évf. 11 sz. 3. pp. 94-101, 2021

[S13] D. Matusz-Kalász, I. Bodnár, R.R. Boros, *Range-Reducing Effect of Contaminants in Case of Solar Vehicles,* Lecture Notes in Mechanical Engineering 22 pp. 38-48, 2021 **(SCOPUS)**

[S14] I. Bodnár, R.R. Boros, D. Matusz-Kalász, *Solar powered electric car with VVVF drive control,* GÉP évf. 71, sz. 3-4, pp. 55-60, 2020

[S15] D. Matusz-Kalász, *Napelemről táplált vízszivattyú mezőgazdasági felhasználásának lehetősége,* Doktoranduszok Fóruma, Miskolc, 2019. november 21. Gépészmérnöki és Informatikai Kar Szekciókiadványa, Miskolci Egyetem Tudományos és Nemzetközi Rektorhelyettesi Titkárság, 188 p. pp. 122-126.

[S16] I. Bodnár, D. Matusz-Kalász, *Napelemek laboratóriumi és szimulációs vizsgálata,* Multidiszciplináris Tudományok, vol. 9 no. 4. pp. 261-268, 2019

[S17] I. Bodnár, D. Matusz-Kalász, M. Bíró, *Napelemes erőmű feszültségviszonyai,* ENELKO 2019 SzámOkt 2019, XX. Nemzetközi Energetika-Elektrotechnika Konferencia, XXIX. Nemzetközi Számítástechnika és Oktatás Konferencia, Kolozsvár, Románia, Erdélyi Magyar Műszaki Tudományos Társaság (EMT), (2019) pp. 8-13.

6. LITERATURE CITED IN THE THESES BOOKLET

[1] J. Alonso-Montesinos, F.R. Martínez, J. Polo, N. Martín-Chivelet, F.J. Batlles, *Economic effect of dust particles on photovoltaic plant production,* Energies, vol. 13, no. 23, 6376, 2020, doi: 10.3390/en13236376

[2] H.A. Kazem, M.T. Chaichan, A.H.A. Al-Wael, K. Sopian, *A review of dust accumulation and cleaning methods for solar photovoltaic systems,* Journal of Cleaner Production, vol. 276, 123187, 2020, doi: 10.1016/j.jclepro.2020.123187

[3] I. Bodnár, P. Iski, D. Koós, Á. Skribanek, *Examination of electricity production loss of a solar panel in case of different types and concentration of dust,* in M. Al Ali, M. Platko (Eds.): Advances and Trends in Engineering Sciences and Technologies III, Taylor & Francis Group: London, UK, pp. 313-318, 2019, doi: 10.1201/9780429021596

[4] Z. Kherici, N. Kahoul, H. Cheghib, M. Younes, B.C. Affari, *Main degradation mechanisms of silicon solar cells in Algerian desert climates,* Solar Energy, vol. 224, pp. 279-284, 2021, doi: 10.1016/j.solener.2021.06.033

[5] M.R. Maghami, H. Hizam, C. Gomes, M.A. Radiz, M.I. Rezadad, S. Hajighorbani, *Power loss due to soiling on solar panel: A review,* Renewable and Sustainable Energy Reviews, vol. 59, pp. 1307-1316, 2016, doi: 10.1016/j.rser.2016.01.044.

[6] M. Abderrezek, M. Fathi, *Experimental study of the dust effect on photovoltaic panels' energy yield,* Solar Energy, vol. 142, pp. 308-320, 2017, doi: 10.1016/j.solener.2016.12.040

[7] M. Gürtürk, H. Benli, N.K. Ertürk, *Effects of different parameters on energy—Exergy and power conversion efficiency of PV modules,* Renewable and Sustainable Energy Reviews, vol. 92, pp. 426-439, 2018, doi: 10.1016/j.rser.2018.04.117

[8] S.A.M. Said, G. Hassan, H.M. Walwil, N. Al-Aqeeli, *The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies,* Renewable and Sustainable Energy Reviews, vol. 82, pp. 743-760, 2018, doi: 10.1016/j.rser.2017.09.042

[9] I. Bodnár, *Electric parameters determination of solar panel by numeric simulations and laboratory measurements during temperature transient,* Acta Polytechnica Hungarica, vol. 15, no. 4, pp. 59-82, 2018.

[10] T. Bhattacharya, A.K. Chakraborty, K. Pal, *Influence of environmental dust on the operating characteristics of the solar PV module in Tripura, India,* International Journal of Engineering Research, vol. 4, pp. 141-144, 2015, doi: 10.17950/ijer/v4s3/313

[11] R. Siddiqui, R. Kumar, K.G. Jha, M. Morampudi, P. Rajput, S. Lata, S. Agariya, G. Nanda, S.S. Raghava, *Comparison of different technologies for solar PV (Photovoltaic) outdoor performance using indoor accelerated aging tests for long term reliability,* Energy, vol. 107, pp. 550-561, 2016, doi: 10.1016/j.energy.2016.04.054

[12] F. Hussain, M.Y.H. Othman, B. Yatim, H. Ruslan, K. Sopian, Z. Anaur, S. Khairuddin, *Fabrication and irradiance mapping of a low cost solar simulator for indoor testing of solar collector,* Journal of Solar Energy Engineering, vol. 133, no. 4, 044502, 2011, doi: 10.1115/1.4004548

[13] P. Singh, N.M. Ravindra, *Temperature dependence of solar cell performance—An analysis,* Solar Energy Materials and Solar Cells, vol. 101, pp. 36-45, 2012, doi: 10.1016/j.solmat.2012.02.019

[14] Kádár, P.; Varga, A. Measurement of spectral sensitivity of PV cells. In 2012 IEEE 10th Jubilee International Symposium on Intelligent Systems and Informatics, Subotica, Serbia, 20-22 September 2012; pp. 549-552.

[15] S.A. Sadat, J. Faraji, M. Nazififard, A. Ketabi, The *experimental analysis of dust deposition effect on solar photovoltaic panels in Iran's desert environment,* Sustainable Energy Technologies and Assessments, vol. 47, 101542, 2021, doi: 10.1016/j.seta.2021.101542

[16] S. Oh, B.W. Figgis, S. Rashkeev, *Effect of thermophoresis on dust accumulation on solar panels,* Solar Energy, vol. 211, pp. 412-417, 2020, doi: 10.1016/j.solener.2020.09.053

[17] M. Cubukcu, A. Akanalci, *Real-time inspection and determination methods of faults on photovoltaic power systems by thermal imaging in Turkey,* Renewable Energy, vol. 147, pp. 1231-1238, 2020, doi: 10.1016/j.renene.2019.09.075

[18] M.U. Ali, S. Saleem, H. Masood, K.D. Kallu, M. Masud, M.J. Alvi, A. Zafar, *Early hotspot detection in photovoltaic modules using color image descriptors: An infrared thermography study,* International Journal of Energy Research, vol. 45, pp. 1-12, 2021, doi: 10.1002/er.7201

[19] O.E. Ikejiofor, Y.E. Asuamah, H.O. Njoku, S.O. Enibe, *Detection of hotspots and performance deteriotations in pv modules under partial shading conditions using infrared thermography,* Engineering Proceedings, vol. 2, no. 1, 71, 2020, doi: 10.3390/ecsa-7-08201

[20] V.S.B. Kurukuru, A. Haque and M.A. Khan, A.K. Tripathy, *Fault Classification for Photovoltaic modules using Thermography and Image Processing,* in 2019 International Conference on Computer and Information Sciences (ICCIS), 03-04 April, 2019, Sakaka, Saudi Arabia, pp. 1-6, doi: 10.1109/ICCISci.2019.8716442

[21] A. Gerber, V. Huhn, T.M.H. Tran, M. Siegloch, Y. Augarten, B.E. Pieters, U. Rau, *Advanced large area characterization of thin-film solar modules by electroluminescence and thermography imaging techniques,* Solar Energy Materials and Solar Cells, vol. 135, pp. 35-42, 2015, doi: 10.1016/j.solmat.2014.09.020S.

Luciani, G. Coccia, S. Tomassetti, M. Pierantozzi, G. Di Nicola, *Use of an Indoor Solar Flash Test Device to Evaluate Production Loss Associated to Specific Defects on Photovoltaic Modules,* International Journal of Design & Nature and Ecodynamics, vol. 15, no. 5, pp. 639-646, 2020, doi:10.18280/ijdne.150504