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PHOTOVOLTAIC MODULES DEGRADATION AND REPOWERING SOLUTIONS ANALYSIS

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Abstract: The paper presents the analysis and evaluation of the photovoltaic module's degradation taking into account the different defects typology that occurred during the 7 years operation period of a photovoltaic installation. The evaluation of the power degradation of photovoltaic modules was done based on onsite measurements and laboratory validation. Two main repowering solutions for the photovoltaic modules were conducted in order to determine the performance improvement of each solution and identifying the financial benefits of applying the repowering solutions to existing photovoltaic installations.
Keywords: power degradation, repowering, performance evaluation, photovoltaic installation, module defects

1. INTRODUCTION

The lifespan of photovoltaic modules is about 25–30 years, but this does not mean that after 25 years (*Romero–Cadaval E., et al., 2013*) it ceases to produce electricity – it only means that energy production falls significantly or falls below the limit at which the operation of the power plant becomes unprofitable (*NREL, 2018*).

Several researchers focus on smart grids (*Miron C., et al, 2019*) and advanced control logic (*Naoui M.A., et al, 2020*) to improve performance of the photovoltaic systems during operation (*Jordan D.C., et al, 2012*), but the current paper takes a different approach (*Ye J.Y., et al, 2014*) and analyzes the performance degradation of photovoltaic modules with emphasis on the current–voltage parameters values from pre–mature ageing process (*Smith R.M., et al, 2012*). The degradation rate is the annual decline in power, expressed as a percentage, compared to the rated power of photovoltaic panels – the power written on its label called peak power, measured at the factory by their manufacturers under STC (Standard Technical Measurement Conditions).

Silicon photovoltaic modules represent more than 80% of the total photovoltaic modules installed globally and over 98% of those installed in ground mounted installations (*Jordan D.C., et al, 2016*) and it's natural that this should be the main focus of study (*Dirk C.J, et al, 2013*). TUV Rheinland is the undisputed leader in the process of qualification and certification of photovoltaic modules as well as in the certification of materials and products that are part of photovoltaic installations.

2. DEFECTS CLASSIFICATION BASED ON OPERATION PERIOD

The ageing and failure mechanisms observed in recent decades have been studied on a wide range of sites and on different sets of materials. Defects may be caused by the quality of the materials, by the defective design of the product or by non–compliance with the quality monitoring procedures on the production line. Figure 1 shows the failure and aging mechanisms of photovoltaic modules that occur in the three stages of life: in the first period – infant mortality, in the first 4–5 years – average life period, up to 10–12 years – usually warranty period and the last period, the period of wear (*IEA–PVPS, 2014*).

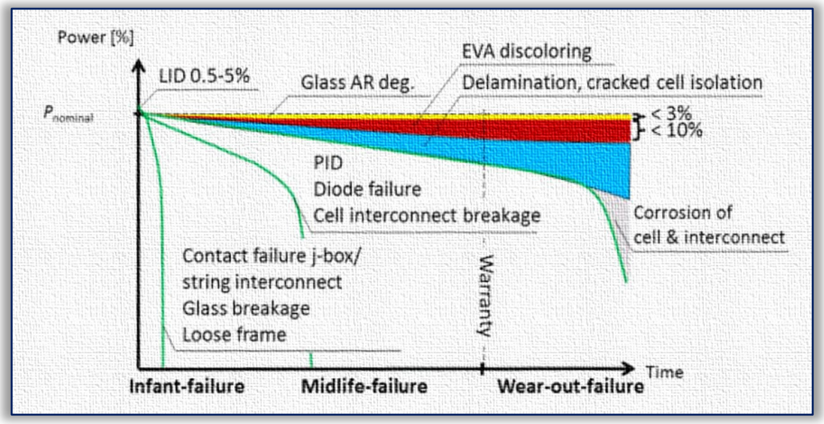

Figure 1. Typical failure scenario of crystalline photovoltaic modules (IEA–PVPS, 2014)

Defects in photovoltaic modules may have external causes or may be intrinsic, due to non–compliant materials, due to non–compliant processing, or due to poor quality supervision on the technological flow of production. Usually, in the case of photovoltaic modules, all these defects are hidden, but they become visible, or measurable, over the three lifetimes described in Figure 1. Early (or infantile) failures occur at the beginning of the life of photovoltaic modules. The interruption of the life cycle that takes place in the average life period (up to

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10–15 years of operation) is called mid–life failure and at the end of the life period, the wear effects of the photovoltaic modules appear.

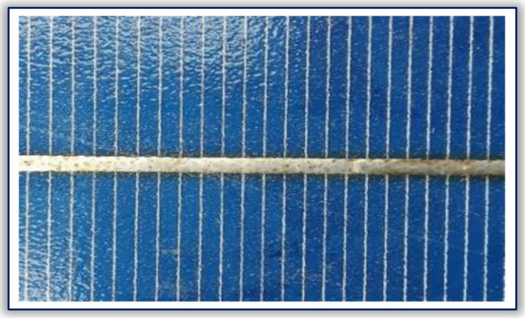
Defects due to external causes, are generated by the improper design of electrical and / or mechanical installations, by improper execution of construction works, including materials transport or are generated by lack of preventive maintenance of the photovoltaic installation.

- Defects of the mounting structure: These are defects that result of improper design or execution of the mounting structure or in other cases, the structure foundation is non–compliant and the alignment of the photovoltaic modules has changed over time (*Haque A., et al, 2019*).
- Defects caused by transport or improper handling during installation: There are often situations in which the photovoltaic modules are installed with the cells cracked during transport (most often invisible) or with the back sheet foil scratched or hit. The cracked cell, if the crack occurred transversely, can evolve and interrupt the string at a given time, which affects the performance of the module and even the entire string of which it is part (*Naveen V.S., et al, 2020*).
- Module interconnection defects: There situations in which the connections are made tense and the crimping of the cable in the connector fails or sometimes the crimping is done improperly. In this case, the contact resistance increases, which leads to the cable burning or broken module connection (*Houssein A., et al, 2010*).
- Defects caused by shade modules (plants, bird droppings or snow): There are defects frequently encountered in most photovoltaic installations. The hot spot can lead to the burning of the encapsulation and the back sheet foil, even to the irreversible destruction of the crystalline structure of the photovoltaic cell and / or staining of the encapsulation.

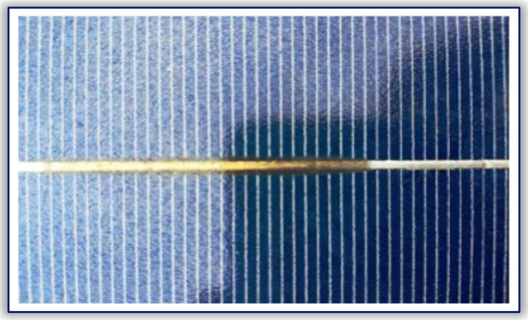
3. SELECTIVE VISUAL ANALYSIS OF PHOTOVOLTAIC MODULES

Together with my team, we carried a selective visual inspection on a number of over 30 rows of panels, distributed in different areas of the photovoltaic installation, the existence of repeated defects was found. Most common defect found, was the color change of one or more ribbons that affect the connection between the cells of the photovoltaic module.

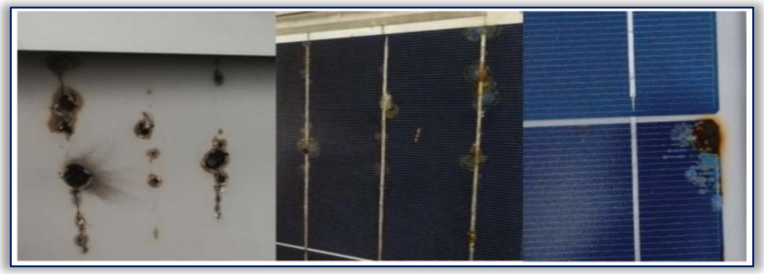
This defect occurs in different stages of evolution and starting with the incipient phase, continues to back sheet marks together with cells connection break and culminating with the last degradation phase (figure 2 a–d) which leads to the burning of the multilayer protective foil (back sheet foil), the breaking of the panel glass or the interruption of the electrical connection between the module cells. The burning of the protective foil can lead to fire (*Danu A., et al, 2018*).



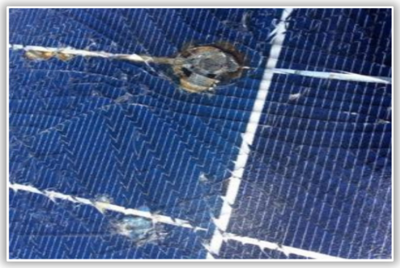
(a) 1st stage defect



(b) 2nd stage defect



(c) 3rd stage defect – preceding the glass breaking and / or cell connections break



(d) 4th stage defect – glass break

Figure 2 – Defect evolution stages of photovoltaic modules (Danu A., et al, 2018)

In figure 3 are presented some images taken by me and my team with an infrared camera that indicates the temperature of the hot spot on the photovoltaic modules, due to vegetation.

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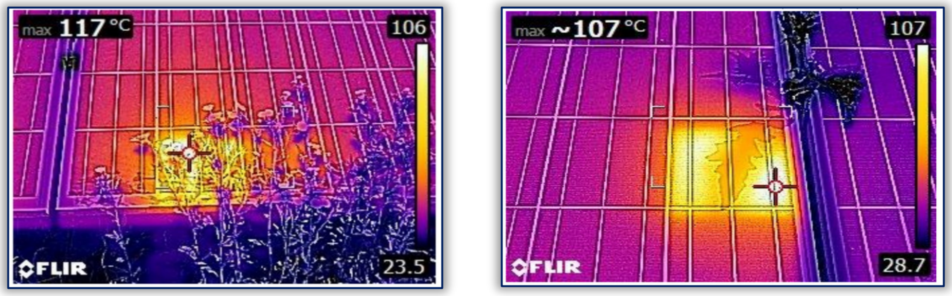

Figure 3 – Hot point for vegetation in front of the module (left) and between module (right) (*Chiriac G., et al, 2017*)

The defects presented above have been found to be a maintenance defect that affects the photovoltaic modules over time if prompt remedial action is not taken. This will lead to the creation of hot spots (HOTSPOT) on modules caused by the partial shading of cells by excessively grown vegetation in the vicinity of the panels or through the spaces between the panels (*Chiriac G., et al, 2018; Miguel G., et al, 2013*).

4. REPOWERING ASPECTS OF PHOTOVOLTAIC INSTALLATIONS

Repowering is the process of replacing defective photovoltaic modules and / or modules that show a premature power degradation with new modules, but of the same type and with rated powers equal to the original module. The most common technical reason for repowering is the so–called degradation of the power of the modules, which produces in time, for each module a loss of their power during operation. The causes are various: climatic conditions, use of non–compliant materials in the manufacturing process, maintenance deficiencies and others.

The power degradation of photovoltaic module is a recognized and inevitable process accepted by everyone within the limit of 0.8% per year (*Murgescu I., et al, 2018*). This value comes from the fact that all manufacturers offer a minimum performance guarantee for photovoltaic modules that states: at least 80% of the rated power after 25 years of operation (figure 4).

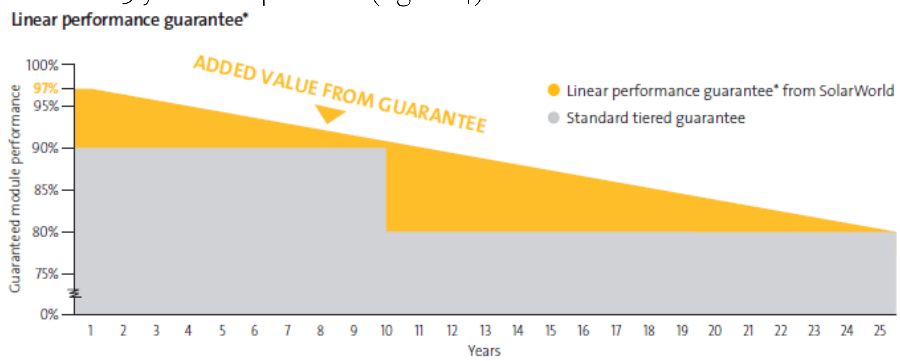

Figure 4 – Performance guarantee model and the decrease evolution of the photovoltaic modules power over time (https://www.solarelectricsupply.com/solar–panels/solar–world)

As a basic rule, if the power of a photovoltaic module decreases by more than 0.8% per year, it is necessary to check the technical parameters of the modules and inverters, by considering the technically and economically profitability of the repowering solution.

The main repowering solutions available now are focused on 2 main components: the photovoltaic modules and solar inverters (*Johns H., 2015*). The photovoltaic modules that represent the best candidate for repowering are the ones with a significant power degradation (over 10%), well below the performance limit corresponding to years of operation or defects that endanger their and string operation.

5. EVALUATION OF PHOTOVOLTAIC MODULES DEGRADATION FOR REPOWERING

For the application of the described repowering solution in 7 years old photovoltaic installation with 245Wp modules, onsite and laboratory measurements were made in order to evaluate the state of the 3660 photovoltaic modules connected to 30 grid inverters. Taking into consideration that the measurement of 3660 will be very time consuming, the focus was to first discover the solar inverters that have a more than 2% variation of energy between group of inputs, which indicates there are modules with higher degradation in their strings.

From this approach, I managed to narrow the search to 2 out of the 30 inverters analyzed and make the measurements of photovoltaic modules on them first onsite (table 1) and select a limited number of modules for laboratory testing. In figure 5, 6 are presented the onsite measurements values for INV6&7.

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Table 1. Measured average degradation of photovoltaic modules in INV6&7 strings

No.	String 1	String 2	String 3	String 4	String 5	String 6
INV 6	–15,98%	–15,62%	–12,94%	–13,56%	–16,32%	–17,33
INV 7	–10,81%	–15,18%	–9,78%	–11,82%	–14,45%	–10,43

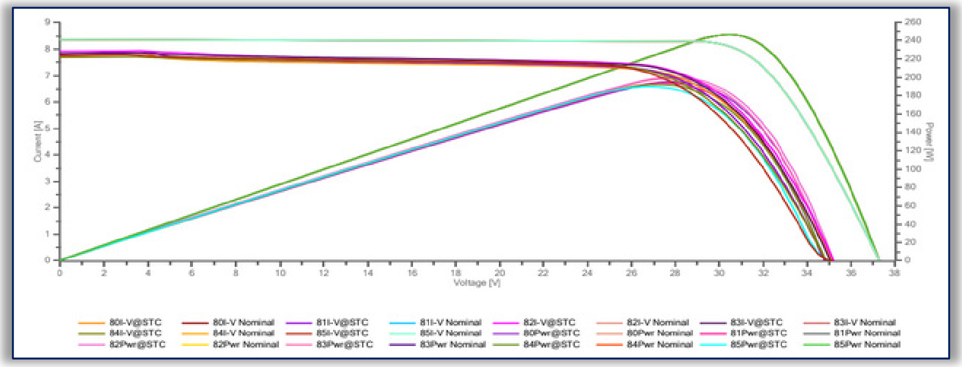

Figure 5 – Onsite measurements values for INV6 (I–V400–1000V/15A I–V)

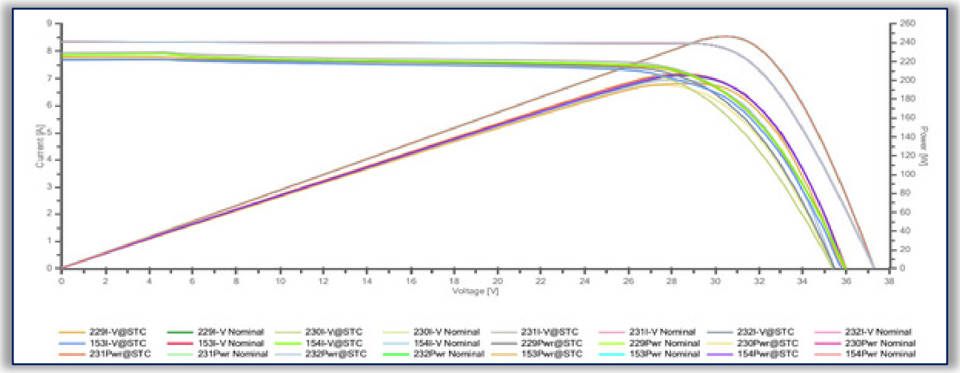

Figure 6 – Onsite measurements values for INV7 (I–V400–1000V/15A I–V)

Based on the measurements presented in table 1, the repowering solution for each inverter is: for INV6 with a higher average module degradation value, the solution is to replace all photovoltaic modules with new modules with the same technical characteristics and for INV7 with a lower average module degradation value, the solution is to measure and replace only the photovoltaic modules with low performance.

For INV7, the modules with problems were identified and replaced in order to minimize mismatch losses between the modules on all 6 strings of the inverter. The results identified a number of 12 modules replaced with existing modules with good performance from INV6 (inverter that was completely replaced) and there was no need to replace modules in string 1 (table 2). The average degradation of the replaced photovoltaic modules was –31,26%, as opposed to –13,97 % after the module replacement, which represents a power gain of 477W (approx. +25,2%) only for the replaced modules and a total gain for the repowering solution of INV7 of 7,7% based only on 12 replaced modules.

Table 2. Measurement of photovoltaic modules before and after replacement in INV7

No.	String	Module	Before measurement		After measurement	
			Value [W]	Degradation [%]	Value [W]	Degradation [%]
1	2	17	183,56	–19,96	199,91	–12,93
2	2	21	164,56	–28,24	195,47	–14,74
3	3	15	147,00	–35,90	194,83	–15,94
4	4	3	164,87	–28,11	195,72	–14,65
5	4	6	119,48	–47,90	196,47	–14,33
6	4	13	171,60	–25,17	196,82	–14,17
7	4	14	167,63	–26,90	198,76	–13,33
8	4	16	163,95	–28,50	201,59	–12,09
9	5	12	178,01	–22,37	199,07	–13,19
10	5	13	157,87	–31,16	197,04	–14,08
11	5	17	142,45	–37,88	199,36	–13,07
12	6	13	130,64	–43,03	194,52	–15,17

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For validation purposes a batch of 6 photovoltaic modules from INV6&7, were also measured in the specialized Photovoltaic Testing Laboratory at INCDIE ICPE–CA, where the current–voltage curve was determined (table 3).

Table 3. Measurement of photovoltaic modules in laboratory

No	Module SN	Vmp[V]	Imp[A]	P[W]
A.	201301210447	28,433	7,367	209
B.	201301401847	28,403	7,365	209
C.	201301402276	28,995	7,239	210
D.	201301413403	28,364	7,394	210
E.	201301414171	23,403	7,134	167
F.	201301414174	21,957	7,067	155

For the repowering solution for INV6, taking into consideration that all modules were replaced with 245Wp modules with the same performance as originally installed, the results show a performance gain much higher of about 23,05%, based on a 3–day measurement campaign on–site (table 4).

Table 4. Energy measurement before/after repowering solution for INV 6/day – all modules replaced

No	Measurement	Before Repowering [W]	After Repowering [W]	Performance Gain [%]
1.	String 1	11.971	15.489	22,71%
	String 2	12.001	15.430	22,22%
2.	String 1	11.533	15.126	23,75%
	String 2	11.546	15.039	23,23%
3.	String 1	11.339	14.794,5	23,36%
	String 2	11.330,5	14.723	23,04%

From the analysis of the string measurements done for all 30 inverters, the average degradation per string for the photovoltaic system is –13.85%, with the minimum degradation of –8.78% for INV11. Based on the performance guarantee model and the decrease evolution of the photovoltaic modules power over time and by subtracting 3% which is the degradation of LID (Light Induction Deterioration) allowed by manufacturers and customers, which occurs in the first year after installation, the degradation result for the entire system is (13,85%–3%)/7years = 1.55%/year. The value is almost double from the 0,8%/year limit.

The degradation value of –8,78% found in INV11, is very close to the –8,6% normal degradation limit calculated for a 7 years photovoltaic installation. The average degradation per string is closely matched with the degradation measured for the modules replaced in INV7 as part of the repowering solution, thus validating the above results for both repowering solutions applied.

6. ECONOMIC ANALYSIS OF THE REPOWERING SOLUTION

In order to identify the economic feasibility of the repowering solutions proposed, a complex analysis of the performance of all inverters was made, in order to have a hierarchy. The optimum repowering solution is a mix of: replacing all modules for 17 inverters, rearranging to reduce mist–match losses for 8 inverters and keeping the current configuration of 5 inverters. The economic analysis was done for a 15–year period, based on the following premises: the investment value for the repowering solution, only the surplus energy supplied to the grid after repowering and the current and future energy price (table 5).

Table 5. Results of the economic indicators for the repowering solution

Investment value for repowering	112.000	EUR
Net Present Value (NPV)	79.840	EUR
Internal Rate of Return (IRR)	10,7	%
Profitability Index (PI)	1,28	–
Recovery Term (RT)	8,8	years

The analysis of the determined efficiency indicators shows that the project is profitable because the financial discount rate considered has a positive NPV, the calculated internal rate of return is higher than the financial discount rate and the profitability index supraunitary under the specified conditions of the analysis.

7. CONCLUSIONS

The paper presents the evaluation of photovoltaic modules degradation taking into account the different defects typology that occurred during the 7 years operation period of a photovoltaic installation, with 3660 photovoltaic modules of 245Wp and 30 grid inverters. Repowering solution for restoring power to initial values were defined and 2 main approaches were conducted: replacement of all photovoltaic modules for INV6 with new modules with the same technical characteristic and replace only low performance photovoltaic modules for INV7.

The measurement result shows an average total degradation of –13,85% for the photovoltaic system, validated with a batch of laboratory measurements as well. The performance degradation value found of 1,55%/year is much higher than normal and will continue to affect in a negative way the performance of the photovoltaic system in the following operation period, if no intervention will occur. The repowering solutions results show a performance improvement of 7,7% for the INV7 (only low performance photovoltaic modules were replace, with modules from INV6) and 23,05% for the INV6 (replaced with all new photovoltaic modules).

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The economic analysis of the repowering solution proposed, shows the that project is profitable, with a net present value of 79.840 over 15 years and an 8,8 years recovery term of the investment, with the profitability index supraunitary.

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References

[1] E. Romero–Cadaval, G. Spagnuolo, L. G. Franquelo, C. A. Ramos–Paja, T. Suntio, W. M. Xiao, "Grid–Connected Photovoltaic Generation Plants: Components and Operation," in IEEE Industrial Electronics Magazine, vol. 7, no. 3, pp. 6–20, Sept. 2013, doi: 10.1109/MIE.2013.2264540.
[2] ***NREL, “Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems”, Technical Report NREL/TP–7A40–73822, 2018
[3] C. MIRON, S. OLTEANU, N. CHRISTOV, D. POPESCU. “Advanced control system for photovoltaic power generation, storage and consumption”, U.P.B. Sci. Bull., Series C, Vol. 81, Iss. 3, 2019 ISSN 2286–3540
[4] M.A. NAOUI, B. LEJDEL, M. AYAD, “Integrating iot devices and deep learning for renewable energy in big data system” U.P.B. Sci. Bull., Series C, Vol. 82, Iss. 3, 2020 ISSN 2286–3540
[5] Jordan, D C; Wohlgemuth, J H; Kurtz, S R, “Technology and Climate Trends in PV Module Degradation” 27th European Photovoltaic Solar Energy Conference and Exhibition, 24–28 September 2012, NREL/CP–5200–56485.
[6] J. Y. Ye, T. Reindl, A. G. Aberle and T. M. Walsh, "Performance Degradation of Various PV Module Technologies in Tropical Singapore," in IEEE Journal of Photovoltaics, vol. 4, no. 5, pp. 1288–1294, Sept. 2014, doi: 10.1109/JPHOTOV.2014.2338051.
[7] Smith, Ryan M.; Jordan, Dirk C.; Kurtz, Sarah R., “Outdoor PV Module Degradation of Current–Voltage Parameters”, Renewable Energy Forum, May 2012, NREL/CP–5200–53713.
[8] D. C. Jordan, M. G. Deceglie and S. R. Kurtz, "PV degradation methodology comparison — A basis for a standard," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), 2016, pp. 0273–0278, doi: 10.1109/PVSC.2016.7749593.
[9] Dirk C. Jordan and Sarah R. Kurtz, “Photovoltaic Degradation Rates — An Analytical Review”, Progress in Photovoltaics Research and Applications 21, 2013, DOI: 10.1002/pip.1182
[10] ***IEA–PVPS, “Review of Failures of Photovoltaic Modules”, Report IEA–PVPS T13–01:2014
[11] A. Haque, V. S. B Kurukuru, A. K. Mohammed, K. Irshad, A. J. Zainul, “Fault diagnosis of Photovoltaic Modules”, Enegy Science & Engineering, Vol. 7, Iss. 3, Pag. 622–644, 2019, doi :10.1002/ese3.255
[12] Naveen Venkatesh S, V Sugumaran “Fault diagnosis of visual faults in photovoltaic modules: A Review”, International Journal of Green Energy, Volume 18, 2021 – Issue 1, Pages 37–50, 2020, doi: 10.1080/15435075.2020.1825443
[13] A. Houssein, N. Héraud, I. Souleiman, G. Pellet, "Monitoring and fault diagnosis of photovoltaic panels," 2010 IEEE International Energy Conference, 2010, pp. 389–394, doi: 10.1109/ENERGYCON.2010.5771711.
[14] A. Danu, D. M. Cocârță, V. Tanasiev, A. Badea. “The influence of dust deposition on the energy performance of the photovoltaics”, U.P.B. Sci. Bull., Series C, Vol. 80, Iss. 3, 2018 ISSN 2286–3540
[15] G. Chiriac, C. Nituca, D. Cuciureanu and I. Murgescu, "Analysis of hot–spots effects on the performances of a photovoltaic system used in Romania," 2017 International Conference on Electromechanical and Power Systems (SIELMEN), 2017, pp. 239–244, doi: 10.1109/SIELMEN.2017.8123325
[16] G. Miguel, L. Marroyo, Pigueiras E., Marcos, J, Perez M., “Observed degradation in photovoltaic plants affected by hot–spots”, Progress in Photovoltaics: Research and Applications. 22. 10.1002/pip.2393, 2013.
[17] I. Murgescu, L.–A. El–Leathey, R.–A. Chihaia, “Guaranteed versus real service life of PV panels in Romania”, Journal of Engineering Sciences and Innovation Volume 3, Issue 4 / 2018, pp. 375 – 392.
[18] ***https://www.solarelectricsupply.com/solar–panels/solar–world
[19] H. Johns, “Energy Revolution: Your Guide to Repowering the Energy System”, Permanent Publications, 2015, ISBN: 1856231976, 9781856231978
[20] ***I–V400–1000V/15A I–V curve tracer compatible with HTANALYSIS™

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