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Reliability characteristics of first-tier photovoltaic panels for agrivoltaic systems – practical consequences**

Vladislav Poulek[1], *Zdeněk Aleš*[2], *Tomáš Finsterle*[3], *Martin Libra*[4]*, *Václav Beránek*[5], *Lucie Severová*[1], *Radek Belza*[4], *Jaroslav Mrázek*[2], *Martin Kozelka*[4], *Roman Svoboda*[1]

[1]Department of Economic Theories, Czech University of Life Sciences Prague, Kamycka 129, 16500 Prague, Czech Republic
[2]Department of Quality and Dependability of Machines, Czech University of Life Sciences Prague, Kamycka 129, 16500 Prague, Czech Republic
[3]Department of Electrotechnology, Czech Technical University in Prague, Technicka 2, 16627 Prague, Czech Republic
[4]Department of Mathematics and Physics, Czech University of Life Sciences Prague, Kamycka 129, 16500 Prague, Czech Republic
[5]Manager, Solarmonitoring, Ltd., Podebradova 275, 43923 Lenesice, Czech Republic

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A b s t r a c t. A vast majority of PV panel suppliers declare a PV panel lifetime in the range of 20-30 years (typically 25 years). Our data from long-term monitoring of many PV power plants indicate that first-tier PV panels at many PV power plants, in moderate climate, start to fail after about 10-12 years. Compared to standard PV systems, the agrivoltaic systems are exposed to extraordinary influences of agriculture like dust, humidity, vibrations, fertilizers *etc*. Our studies compare the quality of PV panel components within last 25 years. We performed long-term monitoring of 85 PV plants, including agrivoltaics, worldwide too. PV panel failures within strings cause subsequent damage to multistring inverters. As inverters are more expensive than the PV panels, the total expenses for PV panel and PV inverter replacement are growing quickly after 10-12 years of the PV power plant operation. Hence, it is very important to study the reliability characteristics of PV panels to predict their real lifetime and to predict PV power plant service expenses.

K e y w o r d s: photovoltaics, first-tier photovoltaic panel, agrivoltaics, reliability characteristics, Weibull analysis, photovoltaic power plant service expenses

1. INTRODUCTION

The innovative design of photovoltaic systems will enable the dual usage of agricultural land both for the cultivation of crops and at the same time for the production of electricity (Libra *et al*., 2024), Building integrated photovoltaic systems (BIPV) (Poulek *et al*., 2018) are frequent too. The number of building integration photovoltaic system installations continues to increase because it has less limiting installation space (Ha *et al*., 2020; Shukla *et al*., 2017; Božiková *et al*., 2021). Agrivoltaic systems can further expand the area suitable for PV power plants (Libra *et al*., 2024).

Photovoltaic panels (components) installed are to be used for many years as the main components of the photovoltaic system exposed to the external environment. However, reliability and long service life are also required for other reasons, and several reliability testing methods have been developed and implemented to ensure such a goal (Osterwald and McMahon, 2009; Rahman *et al*., 2015).

Photovoltaic modules are composed of various components, and each component should be analyzed from the point of view reliability. The lifetime and reliability of photovoltaic modules depend on possible degradation and failure modes during the photovoltaic module production process, transport, and installation. Years of outdoor exposure carry the risk of wear and failure as moisture penetrates through the component connections or the components themselves (Libra *et al*., 2023). Also snow, dust, wind, corrosive gases, solar irradiance, and possible hail do not help with wear and can cause various problems. It must be taken into

*Corresponding author e-mail: libra@tf.czu.cz
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consideration that panels installed in the Czech Republic do not suffer from the same problems as those used in demanding environments (Quarter *et al*., 2014; Abdallah *et al*., 2023; Aly *et al*., 2020; Singh *et al*., 2022).

Since photovoltaic modules are composed of modules with different thermal expansion coefficients, changes in the installation ambient temperature can cause thermal fatigue, which can lead to failure. Extending the lifespan of photovoltaic modules by improving reliability can reduce maintenance costs and give home users more satisfaction and safety.

The performance of photovoltaic modules should be continuously monitored and evaluated. Typically, the warranty begins on the date of installation and lasts 5 to 25 years, depending on the company, guaranteed under operating conditions. This guarantee applies to 90% peak performance in the first ten years and 80% peak performance by 25 years (Atsu *et al*., 2020; Vazquez and Rey-Stolle, 2008).

When evaluating the reliability of a photovoltaic system, it is essential to take into account not only the PV modules, but also the entire system. An installed PV system can only perform as expected if all its components are functioning as they should and the entire photovoltaic system is professionally maintained (Bajenescu, 2020).

A vast majority of PV panel suppliers declare PV panel lifetime in the range of 20-30 years (typically 25 years). Annual output power degradation typically of 0.6% is declared. Within the last 13 years, the PV panel price was reduced up to 10 times. A part of the price reduction is associated with the large volume production. Another reason for the price reduction is the reduced quantity and quality of materials used. For instance, the frame thickness was reduced from 40-50 to 30-35 mm, and the front glass thickness decreased from 4 to 3 mm for triple area PV panels. The high quality PVF (polyvinyl fluoride) back sheet was changed into PVDF (polyvinylidene fluoride) and later into PET (polyethylene terephthalate) back sheet. Until now, there has been limited information about the reliability of PV panels in real field conditions.

There are reports (Dunlop and Halton, 2006; Skoczek *et al*., 2009) on the long-term performance of PV panels. In moderate climate, the typical annual output power degradation of the quantity and quality of the material used is about 0.7%. Other studies (Miller *et al*., 2013; Kurtz, 2013; Kempe *et al*., 2006; McIntosh *et al*., 2011) on the causes of PV panel failures focused mainly on the EVA (Ethylene Vinyl Acetate) encapsulant and the backside TPT laminate (Tedlar Polyester Tedlar). Thermal decomposition of EVA accelerated by ultraviolet radiation in solar spectra results in formation of acetic acid inside the PV laminate. Acetic acid is a corrosive agent causing substantial corrosion (degradation) of solar cells and contacts.

Another study (Van Dyk *et al*., 2005) investigated delamination damage. Especially edge delamination facilitates water penetration into the PV laminate. Water in combination with acetic acid form a conductive solution, which may result in formation of a discharge channel between the busbars of solar cells and the grounded aluminum PV panel frame. Subsequent reports described the reliability of PV panel front side encapsulation. Many evaluations were performed in hot climate (Bandou *et al*., 2015; Omazic *et al*., 2019; Dhimish and Alrashidi, 2020; Sharma and Chandel**,** 2016; Kim *et al*., 2021; Voronko *et al*., 2021). In tropical climate, the typical annual output power degradation is up to 2%. Therefore, data sheets declaring the annual degradation rates of 0.6-0.7% and lifetime of 25 year are often not realistic.

As we are monitoring many PV power plants in the moderate climate of central Europe (Poulek *et al*., 2021), we have enough data to evaluate the reliability of PV panels within a 12-year period. Some data are presented in this report.

Our analysis of changes in PV panel design parameters is as follows:

2. CHANGING PV PANEL PARAMETERS

2.1. Frames

The average PV panel frame height has been about ~35 mm for many years, but the usual PV panel area is 4 times larger now. The load carrying frame length is double now. The consequences for PV panel frame bending are as follows:

Maximum frame bending depth is:

$$V_{\max} = \frac{5\,ql^4}{384\,EJ_z}\,, \tag{1}$$

where: q is the load (wind or snow), l is the length of the frame, E is Young modulus of elasticity, and J_z is the momentum of inertia.

Lets estimate the PV panel frame cross section and frame material is the same, so $\frac{5}{384\,EJ_z}$ is constant k.

Then $V_{\max} = \frac{5}{384\,EJ_z}\,ql^4 = k\,ql^4$, where l is the length of the frame and q is the load per length unit (own weight, wind, or snow). Recently, the length of the PV panel frame is twice as long as that of a 25-year-old one, so $l_2=2l$. The PV panel wind or snow load per frame length is $q_2=2q$. In this case:

$$V_{\max 2} = 32\ V_{\max}, \tag{2}$$

So the idealized PV panel load carrying frame bending depth is increased 32 times. The approximate estimate indicates substantial reduction of the PV panel frame strength. Theoretically, the PV panel frame could be supported in 3-4 points but all recent manufacturers' installation instructions describe a frame support in 2 points.

Another fact is that originally the frames were always fixed to PV laminates by continuous all around sealing/gluing. Recently, the frames are often fixed to the PV laminate by a few tiny points of glue. There are about four 0.5 cm glue spots within 170 cm of the frame length. Hence, the frame fixing force is reduced substantially. Even more important is that the PV laminate edges are not sealed sufficiently. This results in fast edge delamination failure (Poulek *et al*., 2018).

2.2. Back side polymer laminate

Concerning the PV panel back polymer film laminate, the best quality PVF (Tedlar) film was used originally. Recently, much less durable films like PVDF, PET, PA, PP, etc. have been used. The polymer film thickness has been reduced by about 100 μm. Additionally, the typical PV array system voltage has increased from about 600 V DC to 1500 V DC. Therefore, the quality of insulation/encapsulation materials should be increased rather than decreased.

Finally, many new PV plants have been installed in tropical locations with demanding climate. The result is a fast ground impedance (R_{isol}) decrease in real field conditions caused by degradation of the PV panel back sheet (Fig. 1).

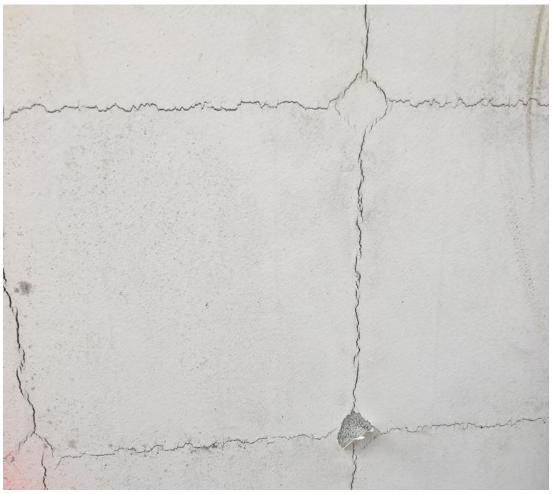

Fig. 1. PV panel back sheet degradation.

2.3. Glass

The PV panel front glass thickness was in the range of 4.0-3.2 mm 25 years ago. Currently, the front glass thickness ranges from 3.2 to 2.8 mm, but the usual PV panel glass area is 4 times larger now. The 2.8 mm thin front glass gives much lower hailstone protection compared to the 4 mm thick glass (Ha *et al*., 2020). In glass/glass PV panels, the usual front glass thickness was 3.2 mm but it has been decreased to 2.0 mm or even to 1.6 mm despite the PV panel area being four times larger.

The troubles with very thin 2.0-1.6 mm glass are as follows:

– The limit glass thickness for standard temperature hardening is 3 mm. Because of technological reasons, thin glass (2 mm or below) is not hardened in a standard way but slightly "improved" only. Cracks in such thin glass are very frequent, namely in large-area PV panels.

– Very thin glass offers low protection to brittle solar cells against hail stones (Ha *et al*., 2020), namely in large-area PV panels.

– The product of the PV panel encapsulating EVA polymer decomposition (acetic acid) cannot escape out of the glass/glass PV panel. On the other hand, the glass/polymer film PV panel design facilitates substantial escape of corrosive acetic acid out of the panel through the thin polymer back sheet.

The changes of the PV panel design will influence the reliability substantially.

As we are monitoring many PV power plants in the moderate climate of central Europe (Poulek *et al*., 2021), we have enough data to evaluate the reliability of PV panels within a 12-year period. Some data are presented in this report.

3. MATERIALS AND METHODS

The Weibull analysis was used for the study of the reliability characteristics of the first-tier photovoltaic panels. We analyzed data from many photovoltaic power plants where our monitoring system SOLARMON (Beránek *et al*., 2018) is used. This method is suitable for studying reliability characteristics. For example, in the paper (Aleš *et al*., 2019), the reliability characteristics of mechanical objects of agricultural machines were calculated according the same international standard (International standard IEC 61649:2008). The reliability data of objects that did not degraded during the monitored period were analyzed.

The authors of the article processed data on photovoltaic panel failures. First-tier photovoltaic panels that had failed became the subject of interest. There were a total of 46 360 photovoltaic panels, with 77.09% failing in the first (1st) stage when the deterioration of the back side TPT laminate started. The edge delamination started at 62.46% of the panels in the second (2nd) stage (some panels had both 1st and 2nd stage failures). The analyzed photovoltaic panels were excluded or censored when they did not fail.

Data for calculation are basically evaluated due to distinction from modified Bernard's approximation. There are primarily two types of data evaluation:

1) Evaluation by time – the test is finished at the specified time T before all objects are defective.

2) Evaluation by failure – the test is finished when the specified number of defects occurred.

The calculation of point estimates of the parameters of the Weibull distribution was performed in several stages:

1) Sorting data in ascending order (time to failure of each panel or operational time in case failure did not occur).

2) Bernard's approximation (calculation for data preparation).

3) Transformation to modified distribution function $F(t)$ (estimation of failure probability).

4) Determination of the equation of the regression straight line.

5) Calculation of the shape α and scale β parameters of Weibull distribution.

First of all, it is essential to sort the evaluated data in ascending order $i = 1, 2, 3, \dots n$. For the estimation of the distribution function of failure probability $F(t)$, modified Bernard's approximation is used (Eqs (3)-(6)). The rank of defects cannot be put into an explicit form; therefore, its value has to be determined by numerical techniques or approximated methods. In a nutshell, the median rank functions transform a collection of ranks i of observed defects to their respective probability of failure in the range from zero to one. A simple analytic approach to the median rank, which has become a standard way of estimation uses Bernard's approximation. The calculation is based on the original Bernard's approximation:

$$F_i(t) = \frac{i-0.3}{n+0.4}\,, \tag{3}$$

where: $F_i(t)$ is the estimation of the average value (-), i is the ascending rank of data point of times to defect t, and n is the total number of defects (Table 1).

On the other hand, the calculation algorithm for failure data is necessary to take into account the influence of evaluated data:

$$i_{t_i} = i_{t_{i-1}} + m_{t_i}\,, \tag{4}$$

$$m_{t_i} = \frac{(n+1)-i_{t_{i-1}}}{1+(n-m)}\,, \tag{5}$$

$$F_i(t) = \frac{i_{t_i}-0.3}{n+0.4}\,, \tag{6}$$

where: m_{ti} is the modified number of PV panel failures, and i_{ti} is the value of the rank in the previous iteration of time to defect t.

When regression analysis is used, the linear Eq. (8) is obtained. This represents the approximation of values by least-square fit of a straight line. The next calculation represents the determination of the shape parameter α and the scale parameter β of Weibull distribution from the distribution function:

$$F(t) = 1 - exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right], \tag{7}$$

and it follows after adjustment:

$$ln\left\{ln\left[\frac{1}{1-F(t)}\right]\right\} = \alpha\ln(t) - \alpha\, ln(\beta). \tag{8}$$

The distribution function $F(t)$ can be converted to the equation of a straight line as follows:

$$b = k\,a + q\,, \tag{9}$$

where: a, b are variables, k is the derivative of the straight line, and q is the intersection of the straight line and the vertical axis.

The a and b values are calculated according to Eqs (10) and (11) (Table 1):

$$a = \ln(t)\,, \tag{10}$$

$$b = \ln\left\{\ln\left[\frac{1}{1-F_i(t)}\right]\right\}. \tag{11}$$

In general, the least squares method (Eqs (12) and (13)) uses a straight line in order to fit through the given points which are known as the method of linear or ordinary least squares. The calculation is based on the following equations:

$$q\sum_{i=1}^{n} a_i + k\sum_{i=1}^{n} a_i^2 = \sum_{i=1}^{n} a_i\, b_i\,, \tag{12}$$

$$n\,q + k\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} b_i\,. \tag{13}$$

The coefficients k and q are based on the following Eqs (14)-(15):

Table 1. Bernard's approximation of the distribution function and the values for the a-axis and b-axis of time to occurrence t (partial data) for the first stage of degradation of photovoltaic panels

Number of occurrence	Adjusted number of failure i_{ti}	Operational time to failure t (year)	Occurrence	Bernard's approximation $F_i(t)$	$a = ln(t)$	$b = ln\left\{ln\left[\frac{1}{1-F_i(t)}\right]\right\}$
…	…	…	…	…	…	…
43209	40264.6	12	Failure	0.8685	2.4849	0.7074
43210	40266.5	12	Failure	0.8685	2.4849	0.7076
43211	40268.5	12	Failure	0.8686	2.4849	0.7078
43212	40270.4	12	Failure	0.8686	2.4849	0.7079
43213	40272.3	12	Failure	0.8687	2.4849	0.7081
43214	40274.3	12	Failure	0.8687	2.4849	0.7082
43215		12	Censored			
…	…	…	…	…	…	…

$$k = \frac{n\sum_{i=1}^{n} a_i b_i - \sum_{i=1}^{n} a_i \sum_{i=1}^{n} b_i}{n \cdot \sum_{i=1}^{n} a_i^2 - \left(\sum_{i=1}^{n} a_i\right)^2}, \tag{14}$$

$$q = \frac{\sum_{i=1}^{n} a_i^2 \sum_{i=1}^{n} b_i - \sum_{i=1}^{n} a_i \sum_{i=1}^{n} a_i b_i}{n \cdot \sum_{i=1}^{n} a_i^2 - \left(\sum_{i=1}^{n} a_i\right)^2} = \overline{b_\iota} - k\,\overline{a_\iota}\,. \tag{15}$$

From the linear regression, we obtain the equation for the linear function in Eq. (16) for the first phase of degradation of photovoltaic panels:

$$a = 0.0782\,b + 2.4475\,. \tag{16}$$

The Pearson's correlation coefficient is significant for verifying the statistical significance of the regression equation. The regression coefficient was calculated and its value is given by Eq. (17) (Rinne, 2008):

$$r^2 = 0.666\,. \tag{17}$$

The Pearson's correlation coefficient takes on values between 0 ÷ 1 (Berrehal and Benisaad, 2016; Garmabaki *et al*., 2016). Values close to 1 correspond to strong dependence, and values close to 0 correspond to weak dependence. According to the international standard (International standard IEC 61649:2008), the *a, b* axes are swapped in our calculation (Fig. 2), *f*(*b*) is usual.

We used Visual Basic for Applications for all the calculations of the parameters of Weibull distribution. Programmed algorithms can be used to easily calculate results when changing input data, which helps to refine reliability characteristics. The field of applications of the Weibull distribution and its relatives is vast and encompasses nearly all scientific disciplines. In addition to applications in engineering sciences, the Weibull distribution can model data in such distinct areas as biological, environmental, health, physical, and social sciences.

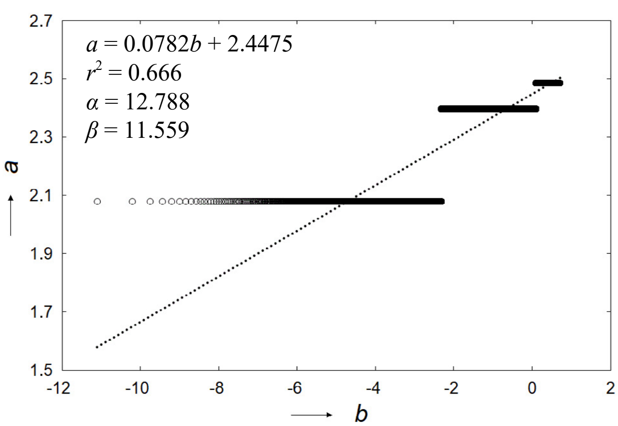

Fig. 2. Graph of calculation of equation of line by linear regression for the first stage of PV panel degradation. Observations of defects. The calculated value of the coefficient of determination $r^2 = 0.666$ indicates that there is a medium correlation between the empirical and theoretical models.

We calculated the values of the parameters of the Weibull distribution *α*, *β* (Fig. 2) according to Eqs (18), (19). These values determine the time *t* to failure for the first phase of PV panel degradation.

$$\alpha = \frac{1}{k} = \frac{1}{0.078201} = 12.788\,, \tag{18}$$

$$\beta = exp(q) = exp(2.4475) = 11.559\,. \tag{19}$$

4. RESULTS AND DISCUSSION

We used the parameters of the Weibull distribution *α*, *β* to calculate the next reliability (lifetime) characteristics: probability density function of failure *f*(*t*), probability of failure *F*(*t*), reliability function *R*(*t*), and failure rate λ(t) (Legát, 2016). For completeness of the reliability characteristics, it is appropriate to mention the calculation of the mean operating time to failure (*MOTTF*) (Eq. (20)).

$$MOTTF = \beta\,\Gamma\left(1+\frac{1}{\alpha}\right) = 11.559\,\Gamma\left(1+\frac{1}{12.788}\right) = 11.103 \text{ years.} \tag{20}$$

For calculation of the mean operating time to failure, it is necessary to use a formula for function *Γ* – GAMMA in MS Excel (Table 2). It can be seen from the obtained reliability characteristics that the increase in the probability of failure is relatively steep, and the monitored photovoltaic panels have a lower reliability then that declared by the producers. This can also be seen in the low value of the mean operating time to failure, which is 11.1 years (Eq. (20)) for the first stage of degradation of photovoltaic panels. An equally important characteristic of reliability is the failure rate, which represents the probability that a photovoltaic panel that has not broken down to operational time *t* will break down immediately after operational time *t* (Legát *et al*., 2017). Too steep a course of the failure rate λ(*t*) is shown in Figs 3 and 4.

In other works, it has already been observed that the real lifetime of PV panels is shorter than the manufacturers declare. See for example Eder *et al*. (2019).

Our data fit well to results from the International Renewable Energy Agency (IRENA). There are substantial consequences for the PV panel recycling industry. Currently, the demand for recycling of PV panels is about 4 times larger compared to optimistic expectations (Cheema

Table 2. Results of the mean operating time to failure (*MOTTF*)

Shape parameter *α*	Scale parameter *β*	Pearson's correlation coefficient r^2	*MOTTF* (year)
First stage			
12.788	11.559	0.6660	11.103
Second stage			
14.131	11.800	0.6597	11.373

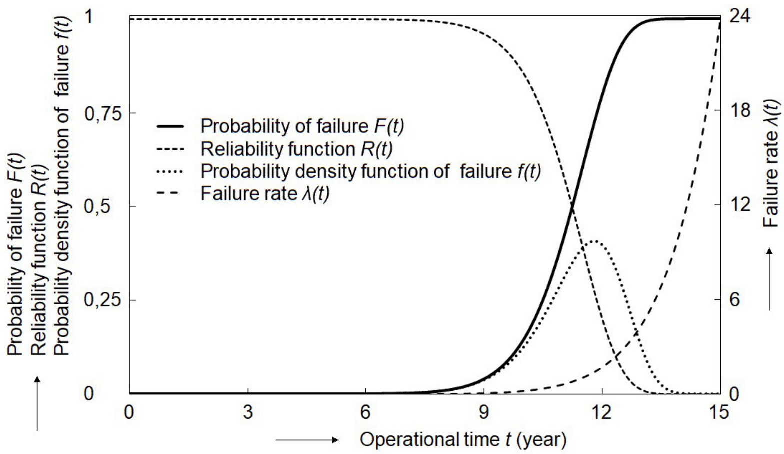

Fig. 3. Reliability characteristics for calculated Weibull distribution for shape parameter $\alpha = 12.788$ and scale parameter $\beta = 11.559$ for the first stage of photovoltaic panel degradation.

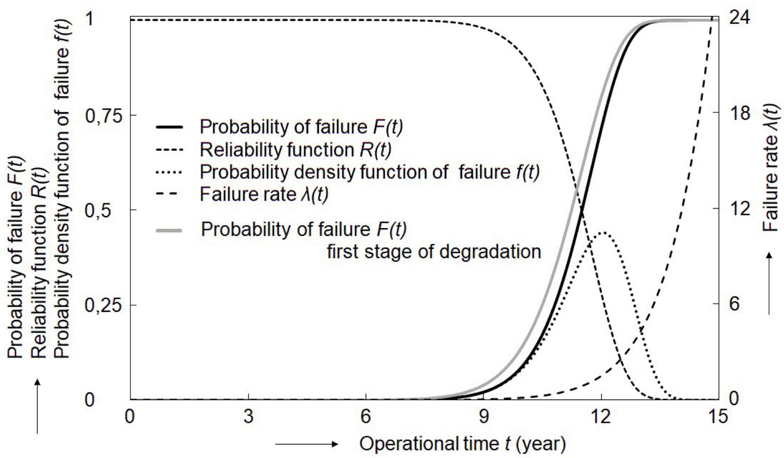

Fig. 4. Reliability characteristics for calculated Weibull distribution for shape parameter $\alpha = 14.131$ and scale parameter $\beta = 11.800$ for the second stage of photovoltaic panel degradation.

et al., 2024). Agrivoltaic systems (Libra *et al*., 2024) are exposed to even higher environmental exposure because of higher dust, humidity, and fertilizers. Figure 5 shows a small agrivoltaic system with vertically arranged bifacial PV panels. The typical PV system with energy storage was described in the article (Poulek *et al*., 2020) and it could be used for agrivoltaic applications as well.

Servicing expenses (PV panel replacement….) of agrivoltaic/photovoltaic power plants start to grow substantially after the 11th year of operation. The relation between servicing expenses and PV power plant owner profits is shown in Fig. 6. The substantial increase in servicing expenses together with the substantial increase in the efficiency of PV panels within the last 15 years supports the phenomenon of repowering of PV power plants. The renovation expenses include: a) the price of the renovation polymer (Polysiloxane gel) and b) workers' wages (Poulek *et al*., 2023).

Fig. 5. Small agrivoltaic system with vertically arranged PV panels in the Czech Republic.

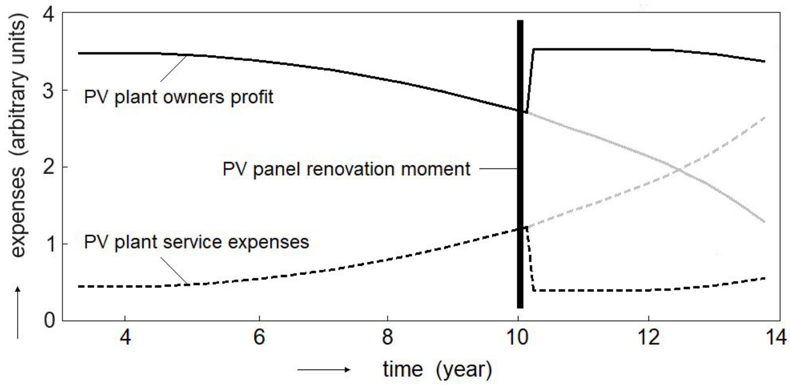

Fig. 6. Comparison between PV power plant owners' profit and service expenses.

5. CONCLUSIONS

We used Weibull analysis to determine the distribution of the failure probability density function $f(t)$ and the failure probability distribution function $F(t)$ to evaluate the reliability data of the first stage PV panels. The use of Weibull analysis has proven successful in a number of previous failure analyses. This is a reliable method for failure statistics and the calculation was performed in accordance with the above-mentioned international standard. The presented analysis is based on an extraordinary set of censored data from the operation of many large photovoltaic power plants. The data were collected over a period of 12 years. From the results, it can be seen that the calculated mean operating time to failure (*MOTTF)* values are relatively low compared to the values declared by the PV panel manufacturers. This is evident from the reliability characteristics in Figs 3 and 4. The data fit well to other recent reliability reports.

Specifically, the first stage of degradation occurs in the eleventh year of operation. The second stage of degradation follows months after the first stage. The first-tier PV panel suppliers declare warranties in the range of 25-30 years. It does not correspond to real field PV panel measurements. It is possible that PV panel lifetime calculations based on laboratory tests are not accurate. The real field PV panel lifetime in agrivoltaic systems seems to be shorter. So far, the results from the performed calculations have shown that the mean operating time to failure of PV panels reach the first stage of degradation around 11 years of operation. Further stages of degradation follow in a relatively short time, within the scale of months.

The obtained Weibull distribution parameters and detailed analysis can be subsequently used to apply the theory of renewal for decision making between preventive maintenance and corrective maintenance based on unit costs. Information about the moment of recovery will be especially valuable for the owners of photovoltaic systems, because they can better calculate the return on the investment period and other important economic indicators based on current economic information. The proposed computational model can be used in real operation to determine the average lifetime of photovoltaic panels, including other reliability characteristics. All calculations are automated using algorithms in Weibull Analysis, so all results are refined with increasing data on failures. An equally important part of monitoring the lifetime of photovoltaic panels is monitoring the economic return on the investment. It is obvious that the lower lifetime of photovoltaic panels will cause lower profitability of the entire photovoltaic power plant. The next step of the research will be focusing attention on all components of agrivoltaic power plants and assessing the overall reliability of the entire system.

Conflicts of Interest: The authors declare no conflict of interest.

6. REFERENCES

Abdallah, A.A., Ali, K., Kivambe, M., 2023. Performance and reliability of crystalline-silicon photovoltaics in desert climate. Solar Energy 249, 268-277, doi:10.1016/j.solener.2022.11.042

Aleš, Z., Pavlu, J., Kučera, M., Legát, V., 2019. Reliability characteristics of mechanical objects of agricultural machines. In proc. 7th Int. Conf. Trends in Agric. Eng. 2019, Prague, 17th-20th September, 26-31, ISBN 978-80-213-2953-9.

Aly, S.P., Ahzi, S., Barth, N., Abdallah, A., 2020. Numerical analysis of the reliability of photovoltaic modules based on the fatigue life of the copper interconnects. Solar Energy 212, 152-168, doi:10.1016/j.solener.2020.10.021

Atsu, D., Seres, I., Aghaei, M., Farkas, I., 2020. Analysis of long-term performance and reliability of PV modules under tropical climatic conditions in sub-Saharan. Renewable Energy 162, 285-295, doi:10.1016/j.renene.2020.08.021

Bajenescu, T.M., 2020. Some Reliability Aspects of Photovoltaic Modules. In: Reliability and Ecological Aspects of Photovoltaic Modules. IntechOpen, doi:10.5772/intechopen.88641, ISBN:978-1-78984-822-9.

Bandou, F., Arab, A.H., Belkaid, M.S., Logerais, P.O., Riou, O., Charki, A., 2015. Evaluation performance of photovoltaic modules after a long time operation in Saharan environment. Int. J. Hydrogen Energy 40(39), 13839-13848, doi:10.1016/j.ijhydene.2015.04.091

Beránek, V., Olšan, T., Libra, M., Poulek, V., Sedláček, J., Dang, M.Q., *et al*., 2018. New monitoring system for photovoltaic power plants' management. Energies 11(10), 2495, doi:10.3390/en11102495

Berrehal, R., Benisaad, S., 2016. Determining the optimal periodicity for preventive replacement of mechanical spare parts. Mechanika 22(2), 156-161, doi:10.5755/j01.mech.22.2.12269

Božiková, M., Bilčík, M., Madola, V., Szabóová, T., Kubík, L., Lendelová, J., *et al*., 2021, The effect of azimuth and tilt angle changes on the energy balance of photovoltaic system installed in the Southern Slovakia Region. Appl. Sci. 11, 8998, doi:10.3390/app11198998

Dhimish, M., Alrashidi, A., 2020. Photovoltaic degradation rate affected by different weather conditions: A Case Study Based on PV Systems in the UK and Australia, Electronics 9(4), 650, doi:10.3390/electronics9040650

Dunlop, E.D., Halton, D., 2006. The Performance of crystalline silicon photovoltaic solar modules after 22 years of continuous outdoor exposure. Progress in Photovoltaics, 14(1), 53-64, doi:10.1002/pip.627

Eder, G.C., Voronko, Y., Oreski, G., Mühleisen, W., Knausz, M., Omazic, A., *et al*., 2019. Error analysis of aged modules with cracked polyamide backsheets. Solar Energy Materials Solar Cells 203, 110194, doi:10.1016/j.solmat.2019.110194

Garmabaki, A.H.S., Ahmadi, A., Ahmadi, M., 2016. Maintenance optimization using multi-attribute utility theory. in: current trends in reliability, availability, maintainability and safety. Cham: Springer Int. Publishing Switzerland, 13-25, ISBN:978-3-319-23596-7.

Ha, S.W., Park, S.H., Eom, J.Y., Oh, M.S., Cho, G.Y., Kim, E.J., 2020. Parameter calibration for a TRNSYS BIPV model using in situ test data. Energies 13(18), 4935, doi:10.3390/en13184935

Cheema H..A, Sadia Ilyas, Heewon Kang, Hyunjung Kim, 2024. Comprehensive review of the global trends and future perspectives for recycling of decommissioned photovoltaic panels. Waste Management 174, 187–202, doi:10.1016/j.wasman.2023.11.025

International standard IEC 61649:2008 – Weibull Analysis, 62 pages.

IRENA (International Renewable Energy Agency), 2016. End-of-life management: Solar photovoltaic panels. Int. Renewable Energy Agency and the Int. Energy Agency Photovoltaic Power Systems. [cit. 2024-04-10], available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09

Kempe, M.D., Jorgensen, G.J., Terwilliger, K.M., McMahon, T.J., Kennedy, C.E., Borek, T.T., 2006. Ethylene-vinyl acetate potential problems for photovoltaic packaging. IEEE 4th World Conf. Photovoltaic Energy Conversion (WCPEC-4), Waikoloa, Hawaii, USA, 7-12 May, ISBN 1-4244-0016-3.

Kim, J., Rabelo, M., Padi, S.P., Yousuf, H., Eun-Chel Cho, E., Yi, J., 2021. A review of the degradation of photovoltaic modules for life expectancy. Energies 14(14), 4278, doi:10.3390/en14144278

Kurtz, S., 2013. Photovoltaic Module Reliability Workshop 2013 - Technical Report NREL/TP -5200-60167. Colorado: NREL, 26-27 Feb 2013. [cit. 2024-05-30], available from: https://www.nrel.gov/docs/fy14osti/60167.pdf

Legát, V., 2016. Management and maintenance engineering (in Czech). Professional Publishing, Prague, 622 p., ISBN:978-80-7431-163-5.

Legát, V., Mošna, F., Aleš, Z., Jurča, V., 2017. Preventive maintenance models – higher operational reliability. Maintenance and Reliability 19(1), 134-141, doi:10.17531/ein.2017.1.19

Libra, M., Mrázek, D., Tyukhov, I., Severová, L., Poulek, V., Mach, J., *et al*., 2023. Reduced real lifetime of PV panels – Economic consequences. Solar Energy 259, 229-234, doi:10.1016/j.solener.2023.04.063

Libra, M., Kozelka, M., Šafránková, J., Belza, R., Poulek, V., Beránek, V., *et al*., 2024. Agrivoltaics: dual usage of agricultural land for sustainable development. Int. Agrophys. 38, 121-126, doi:10.31545/intagr/184175

McIntosh, K.R., Powell, N.E., Norris, A.W., Cotsell, J.N., Ketola, B.M., 2011. The effect of damp-heat and UV aging tests on the optical properties of silicone and EVA encapsulants, Progress in Photovoltaics 19(3), 294-300, doi:10.1002/pip.1025

Miller, D.C., Muller, M.T., Kempe, M.D., Araki, K., Kennedy, Ch.E., Kurtz, S.R., 2013. Durability of polymeric encapsulation materials for concentrating photovoltaic systems. Progress in Photovoltaics 21(4), 631-651, doi:10.1002/pip.1241

Omazic, A., Oreski, G., Halwachs, M., Eder, G.C., Hirschl, C., Neumaier, L., *et al*., 2019. Relation between degradation of polymeric components in crystalline silicon PV module and climatic conditions: A literature review. Solar Energy Materials Solar Cells 192, 123-133, doi:10.1016/j.solmat.2018.12.027

Osterwald, C.R., McMahon T.J., 2009. History of accelerated and qualification testing of terrestrial photovoltaic modules: a literature review. Progress in Photovoltaics 17(1), 11-33, doi:10.1002/pip.861

Poulek, V., Matuška, T., Libra, M., Kachalouski, E., Sedlácek, J., 2018. Influence of increased temperature on energy production of roof integrated PV panels. Energy Buildings 166, 418-425, doi:10.1016/j.enbuild.2018.01.063

Poulek, V., Dang, M.Q., Libra, M., Beránek, V., Šafránková, J., 2020. PV panel with integrated lithium accumulators for BAPV applications – one year thermal evaluation. IEEE J. Photovoltaics 10(1), 150-152, doi:10.1109/JPHOTOV.2019.2953391

Poulek, V., Šafránková, J., Černá, L., Libra, M., Beránek, V., Finsterle, T., *et al*., 2021. PV panel and PV inverter damages caused by combination of edge delamination, water penetration, and high string voltage in moderate climate. IEEE J. Photovoltaics 11(2), 561-565, doi:10.1109/JPHOTOV.2021.3050984

Poulek, V., Tyukhov, I., Beránek, V., 2023. On site renovation of degraded PV panels – Cost and environmental effective technology. Solar Energy 263, 111956, doi:10.1016/j.solener.2023.111956

Quarter, P.B., Grimaccia, F., Leva S., Mussetta, M., Aghaei, M., 2014. Light unmanned aerial vehicles (UAVs) for cooperative inspection of PV plants. IEEE J. Photovoltaics 4(4), 1107-1113, doi:10.1109/JPHOTOV.2014.2323714

Rahman, M.M., Hasanuzzaman, M., Rahim, N.A., 2015. Effects of various parameters on PV-module power and efficiency. Energy Conversion Manag. 103, 348-358, doi:10.1016/j.enconman.2015.06.067

Rinne, H., 2008. The Weibull Distribution: A Handbook. New York: Chapman and Hall/CRC, 808 p. Eng. Technol., Mathematics Statistics, ISBN 9780429142574, doi:10.1201/9781420087444

Sharma, V., Chandel, S.S., 2016. A novel study for determining early life degradation of multi-crystalline-silicon photovoltaic modules observed in western Himalayan Indian climatic conditions. Solar Energy 134, 32-44, doi:10.1016/j.solener.2016.04.023

Shukla, A.K., Sudhakar, K., Baredar, P., 2017. Recent advancement in BIPV product technologies: A review. Energy Buildings 140, 188-195, doi:10.1016/j.enbuild.2017.02.015

Singh, R., Sharma, M., Yadav, K., 2022. Degradation and reliability analysis of photovoltaic modules after operating for 12 years: A case study with comparisons. Renewable Energy 196, 1170-1176, doi:10.1016/j.renene.2022.07.048

Skoczek, A., Sample, T., Dunlop, E.D., 2009. The results of performance measurements of field-aged crystalline silicon photovoltaic modules. Progress in Photovoltaics 17(4), 227-240, doi:10.1002/pip.874

Van Dyk, E.E., Chamel, J.B., Gxasheka, A.R., 2005. Investigation of delamination in an edge-defined film-fed growth photovoltaic module. Solar Energy Materials Solar Cells 88(4), 403-411, doi:10.1016/j.solmat.2004.12.004

Vazquez, M., Rey-Stolle, I., 2008. Photovoltaic module reliability model based on field degradation studies. Progress Photovoltaics 16(5), 419-433, doi:10.1002/pip.825

Voronko, Y., Eder, G.C., Breitwieser, Ch., Mühleisen, W., Neumaiser, L., Feldbacher, S., *et al.*, 2021. Repair options for PV modules with cracked backsheets. Energy Sci. Eng. 9(9), 1583-1595, doi:10.1002/ese3.936