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Most Searched Topics in the Scientific Literature on Failures in Photovoltaic Installations

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Abstract: Photovoltaic installations (PVs) are currently one of the fastest-growing sources of renewable energy. Expanded forms of financial support and higher electricity prices have resulted in a large increase in its installed capacity. PV installations are increasingly being ordered by industry and privates, often for installations capacity of several hundred kilowatts. In addition to the advantages, photovoltaic installations also have drawbacks. One of these is that the increase in the voltage in the power grid leads to the exclusion of individual installations from the grid. An important issue in the operation of photovoltaic installations is also their reliability during their lifetime. The reliability of photovoltaic installations depends on the random nature of the cloud cover as well as the material's mechanical degradations. This paper presents a literature analysis using Citespace software in terms of reliability. A detailed bibliometric analysis has been performed to outline the main drawbacks of the PV installations cited by researchers. This literature review forms the basis for further analysis. The paper also presents a new approach to implementing the Multiple-Criteria Decision Analysis (MCDA) method for assessing the risk of failure of PV panels. The obtained results showed the main interests of scientists in the field of failure analysis of photovoltaic installations and countries having the largest share in research on this issue. The applied Analytic Hierarchy Process (AHP) analysis enables supporting the process of managing photovoltaic installations by analyzing installation operations in terms of reliability as reliability impacts the profitability of investments and operating costs. The proposed method can be used by the operators of photovoltaic installations or farms.

Keywords: photovoltaic; energy; failure; Analytic Hierarchy Process (AHP); Multiple-Criteria Decision Analysis (MCDA)

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1. Introduction

The increase in demand for electricity and the world's dependence on this form of energy, the tense geopolitical situation, and the rising prices of natural resources [1,2], imported very often from countries with unstable political and economic situations [3], is causing an increase in the installed capacity of renewable energy sources [4]. Backyard photovoltaic or wind power plants can significantly increase the security of the energy demand [5]. Expanded forms of financial support [6], in the form of subsidies for installations such as photovoltaic systems or heat pumps [7], are causing a significant increase in installed systems [8]. Investment in sources of electricity, such as photovoltaic panels, can help companies and households during rising energy prices [9].

Since 2004 there has been a gradual increase in the installed capacity of renewable sources. In 2020, the target set by the European Union to achieve a 20% share of renewable energy in total electricity was achieved. According to Eurostat data, in 2020, the share of RES was 21.3%, an increase in 11.7% compared to 2004.

Taking into account the share of renewable energy in the gross final energy consumption, i.e., the extent to which renewable energy is used and the extent to which renewable

fuels have replaced fossil fuels in the case of transportation. The European Union's aim was to achieve a 10% share of renewable energy in transportation by 2020. This aim was met, achieving a RES share of 10.2% in 2020.

Figure 1 shows the percentage share of renewable sources in electricity generation. In 2020, a renewable share of 37.5% was achieved, an increase in 23.14% compared to 2004.

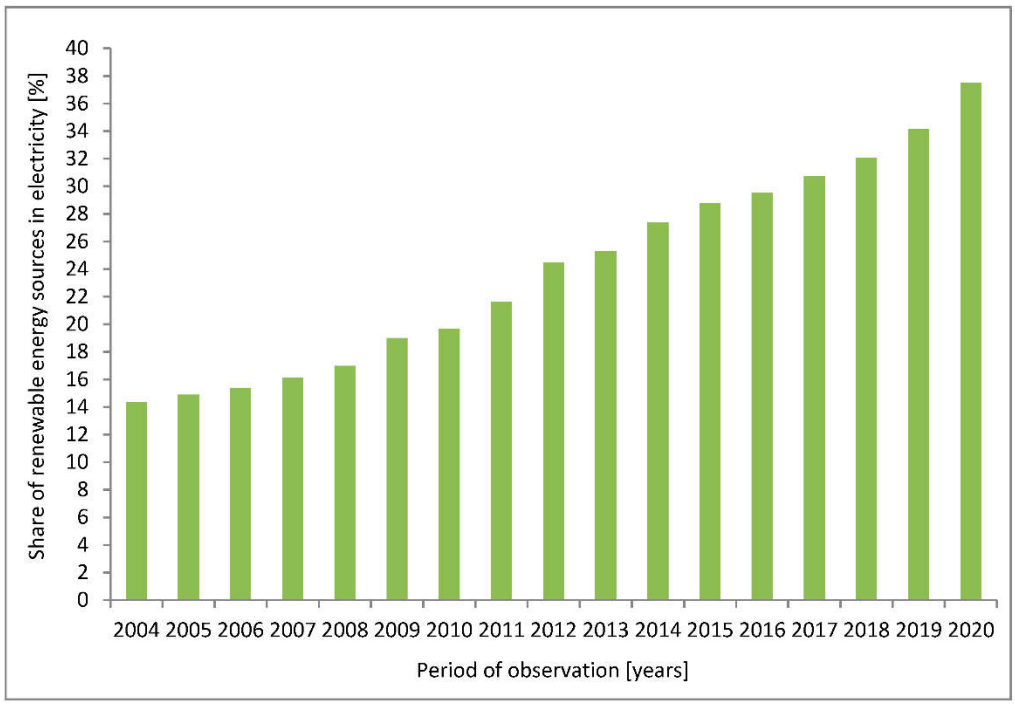


Figure 1. Share of renewable sources in electricity generation, on the basis of [10].

One of the factors through which a high share of renewable energy generation has been achieved is the increase in installed photovoltaic capacity. Figure 2 shows the installed capacity of photovoltaic installations between 2005 and 2020. In 2005, the installed capacity of photovoltaic installations was only 2.17 GW. By 2020, it had already reached 153 GW.

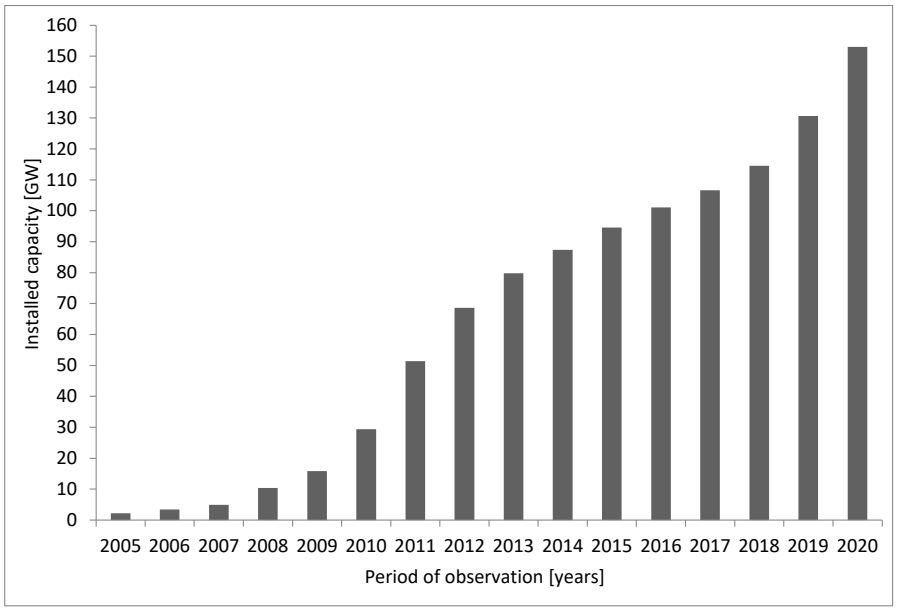


Figure 2. Installed photovoltaic capacity in the European Union, on the basis of [10].

The increasing contribution of photovoltaic systems to electricity generation creates the need to and analyze such systems in terms of their operational reliability.

2. Operation and Failures of Photovoltaic Installations

The operation of photovoltaic power plants and the amount of energy produced depend on the availability and the amount of local solar irradiance, which vary according to cloud cover. Therefore, in the failure and availability analysis of photovoltaic systems, it is necessary to take into account the random nature of cloud cover that directly affects the level of the power output of the photovoltaic panels [11].

A failure is a state in which a system fails to realize its expected function. The failure analysis of a PV installation requires the creation of a model of the installation [12]. A photovoltaic power plant usually consists of photovoltaic panels, an inverter, and the electronics and power electronics that control the plant [13]. Since the output of a photovoltaic power plant depends on the random nature of the cloud cover [14], the plant cannot be represented by a two-state or multi-state model, as these models assume a constant value for the power generated [15].

A photovoltaic installation can have failures that cause the installation to go out of service [16]. The causes of failure can be the following:

- operational:
  - frame stratification [17],
  - increase in resistance and short circuit in cells [18],
  - shading of panels [19],
  - junction box failure [20],
  - PV panels aging [21],
  - a fire in the installation caused by a short circuit [22],
  - degradation of cables insulation [23],
  - improper operational conditions [24],
  - no lightning protection or overvoltage [25],
- environmental:
  - hailstorms, which can damage the panes of glass in the panels [26,27],
  - the heavy or frequent cloudiness [28],
  - poor solar irradiance [29],
  - strong winds [30],
  - fire in the installation caused by lightning [22,25].
- regulatory:
  - solar trackers failure [31],
  - control automatics failure [32].

In countries where the power grid is not geared for distributed energy sources, there may also be a problem with too high a voltage on the grid to which many photovoltaic installations are connected. If the voltage on a phase rises above the limit value, the inverter will disconnect the installation from the grid. If the installation is frequently disconnected, this can have a significant impact on the profitability of the investment [33].

3. Scientometric Analysis of the Literature

Scientometrics has been defined as the "quantitative study of science, communication in science, and science policy" [34]. The main field of interest in this field is the measurement of the impact of scientific articles and journals and the analysis of citations. Current bibliometric mapping software includes, among others: VOSviewer, CitNetExplorer, SCI2, Sci2Tool, Pajek, and Gephi [35]. One of the programs used for the literature analysis is also CiteSpace [36–39], which we decided to use as a research tool due to its universality compared to other software. The CiteSpace 6.1.R3 software was created by Dr. Chen of Drexel University, and it can visualize bibliometric results, show knowledge maps of science development and structural interaction, and identify future research status, research

focuses, and recent developments of disciplines via statistical analysis [40]. Its design and functionalities are based on Kuhn's theory of scientific development model, Price's frontier theory of science, social network analysis theory, structural holes network theory, etc. [41]. The program allows the analysis of the literature from databases such as Web Science or Scopus. In this article, the Scopus database was analyzed. The Scopus database was considered due to its major academic informational content for bibliometric analysis, simplicity of exporting extensive data in groups, and record collection for past citations.

The keywords "photovoltaic failure" was selected as the search criterion. A total of 1363 articles from 1977 to 2022 were selected for analysis. Figure 3 shows the number of publications per year that contain the selected keywords.

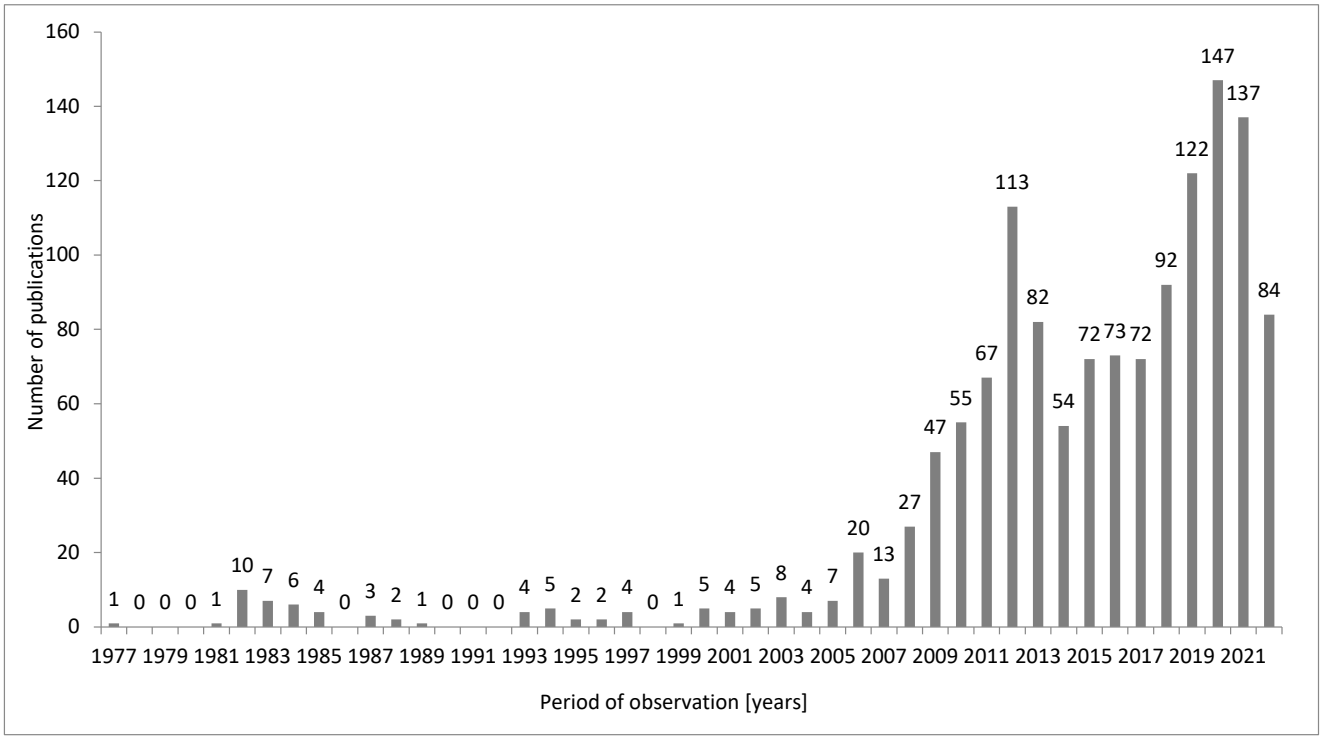


Figure 3. The number of publications per year.

Upon analyzing the graph, it is possible to see an increase in the number of publications since 2006. By comparing Figure 3 with the graph of installed PV capacity (Figure 4), it is possible to see a correlation between the increase in interest in PV and the increase in installed capacity since 2006 with the number of publications analyzing failures and the reliability of such installations.

Figure 4 shows the countries from which the analyzed publications originated and the cooperation between them. Table 1 shows the number of publications from the 20 countries with the highest number of publications and centrality. Centrality is defined for each node in the network. This factor measures the probability that any shortest path in the network will pass through that node. A node with a high centrality value is likely to be in the middle of two large communities or subnetworks [42].

Based on the results, it can be concluded that countries such as the USA, China, Germany, United Kingdom, Spain, and France have a centrality of more than 0.1, which means that they are important centers for PV failure research and are the most important nodes in the structure of cooperation between countries.

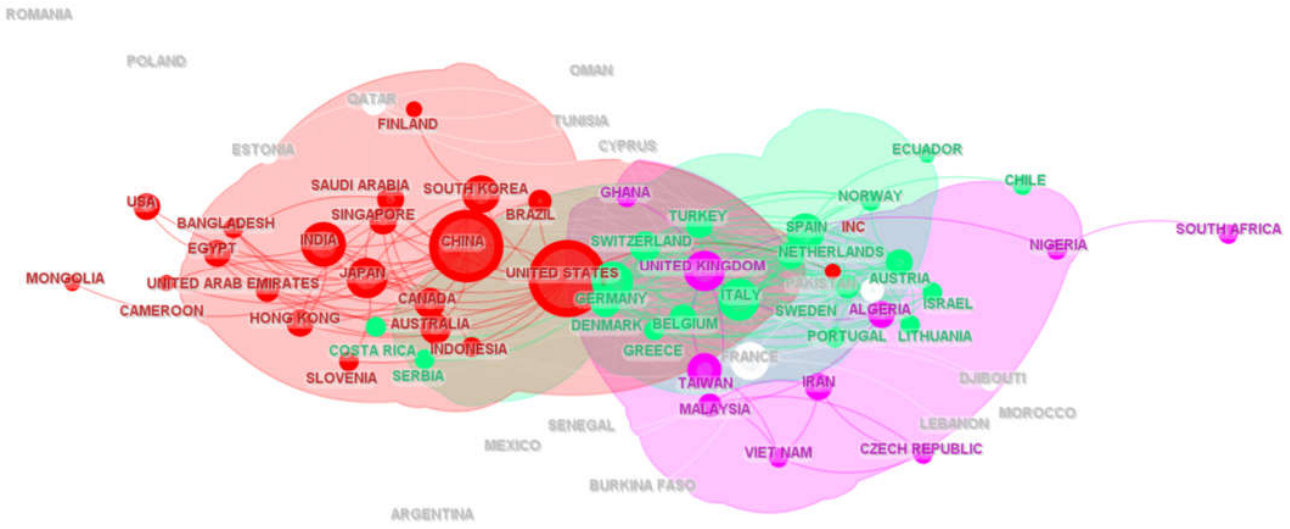


Figure 4. Cooperation between countries.

Table 1. The number of publications and centrality.

Country	Number of Publications	Centrality
USA	331	0.15
China	291	0.11
India	92	0.02
Italy	70	0.04
Germany	64	0.20
Japan	64	0.08
United Kingdom	63	0.18
South Korea	61	0.04
Spain	55	0.12
France	48	0.23
Taiwan	41	0.02
Denmark	31	0.08
Australia	30	0.03
Canada	27	0.06
Switzerland	23	0.02
Netherlands	22	0.02
Algeria	22	0.00
Belgium	18	0.01
Singapore	18	0.00
Austria	18	0.01

Figure 5 shows the analysis of the literature by citation. Citespace analyzed the literature into 11 clusters. Each node in the clusters represents the publications analyzed, while the connections between them define the collaboration between authors and mutual citations.

Table 2 shows the main areas of research interest in the different clusters shown in Figure 5.



Figure 5. Citation analysis.

Table 2. Main research interests.

Cluster ID	Main Interest
#0	Photovoltaic array fault diagnostic, neural network, input fault features, short circuit, non-uniform irradiance
#1	Photovoltaic panels, fault diagnosis models, multiple prediction
#3	Post-fault operation, photovoltaic microconverter, continuous changing operating, continuous changing environmental conditions
#4	PV inverters, small systems, PV system simulation
#5	Bifacial modules, voltage characteristics, various faults
#7	Humidity induced degradation, high temperature, aging techniques
#18	Photovoltaic modules, harsh environment, degradation effects, gradual degradation
#21	Utility scale PV array, current-based protection
#48	Inverters, effectiveness, open-circuit fault in grid connected inverters,
#69	Cell, disconnection, interconnections failure,
#94	Faults diagnosing, monitoring of photovoltaic systems

Figure 6 shows the citation burst for the top 15 publications. The citation burst indicates an increase in the frequency with which an article is cited. It suggests interest in a particular

topic at a particular time or is related, for example, to an influx of citations from publications by Nobel Prize-winning authors. Citation bursts can also signal interest in science over a given period. The higher the strength coefficient, the greater the impact a publication has had on the number of citations by other authors. For example, the publication with the highest strength factor concerns the fault diagnosis technique for photovoltaic systems based on artificial neural networks [43]. The largest increase in interest in this topic, and consequently an increase in citations, began in 2018 and continues today. The second publication deals with the comprehensive review of catastrophic faults in PV arrays, while the third publication deals with real-time fault detection in photovoltaic systems [44,45].

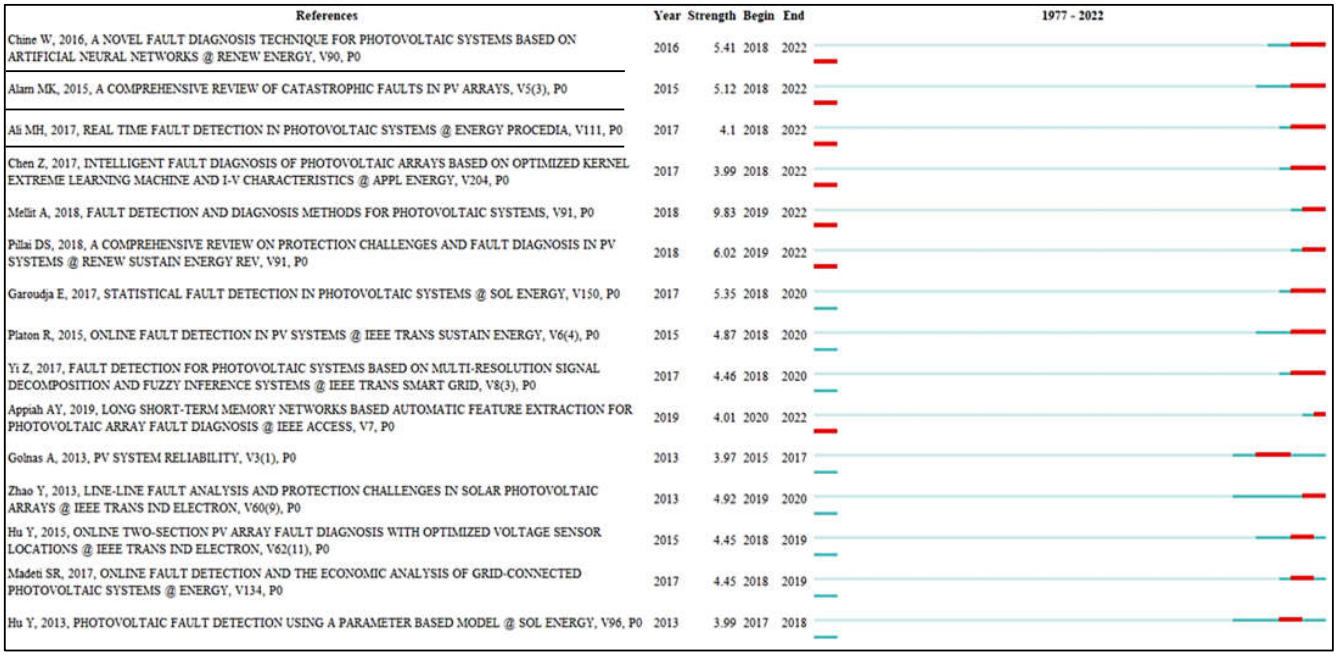


Figure 6. Top fifteen references with strong citation bursts. The underlined references [43–45] are reviewed in the article.

On the basis of the citation burst, it can be concluded that the greatest attention of researchers in the field of PV plant failure is focused on fault diagnosis by different methods and real-time monitoring of photovoltaic systems.

4. Multi-Criteria Decision Analysis with Implementation of Analytic Hierarchy Process of Photovoltaic Panels Failure Risk Assessment

The method is based on a grouping of risk criteria for photovoltaic panels. The assessment is carried out with reference to the designated score values using the Analytic Hierarchy Process (AHP) method [46,47]. In the method under consideration, risk refers to a measure by which one can assess the risks arising from plausible events beyond one's control or from the possible consequences of a decision.

The risk measure is calculated using Equation (1) [48]:

$$r(P) = \sum_{j=1}^{m} p_j \times C_j(P), \quad (1)$$

where r is the additive value of risk, p_j is the point weight for each subcategory criterion j related to design, performance, operational, financial environment or social or surroundings, where $j = 1, 2, \ldots, m$, C_j means the method's consideration of the categories for potential alternatives.

According to the Analytic Hierarchy Process (AHP) introduced by Thomas L. Saaty, each category was given a percentage weight based on how it would affect the risk in-

dex [46]. The procedure for using the AHP involves defining and analyzing the decision problem and setting objectives. A set of criteria is then established, which must be comparable. The next step is to select the appropriate alternatives and determine the consequences of changes in the defined criteria. The outputs are subjected to pairwise comparisons of the selected elements, with a designated advantage of one element over the other, according to a nine-point comparison scale. Finally, the decision is based on the synthesis of the sub-assessments and the selection of the best alternative through the creation of overall rating scales. According to the Saaty scale, individual preferences and specific degrees of advantage are shown in Table 3 [46,47].

Table 3. Scale of relative importance (after Saaty [46,47]).

Interpretation		Value of a_{ij}	Definition
1	1	i and j are equally important	equal importance
2	1/2	equal to moderate importance values	for comprise between the above values
3	1/3	i is slightly more important than j	moderate importance
4	1/4	moderate to strong importance values	for comprise between the above values
5	1/5	i is more important than j	strong importance
6	1/6	strong to very strong importance values	for comprise between the above values
7	1/7	i is far more important than j	very strong or demonstrated importance
8	1/8	very strong to the extreme importance values	for comprise between the above values
9	1/9	i is absolutely more important than j	extreme importance

Assigning a relative preference means that the selection and evaluation of each parameter are more accurate. The expert's judgment is used to increase the substantive representativity of the results. First, the pairwise comparison of criteria allows them to be ordered qualitatively and as a matrix is being constructed quantitatively using values from 1/9 to 9, with seventeen possible evaluations thus provided for.

In pairwise comparisons by reference to an n by n matrix (A), so-called reversible pairwise comparisons are made and can be written as [46,47]:

$$A = [a_{ij}] \text{ for } i, j = 1, \ldots, n \tag{2}$$

where

$$a_{ij} = \frac{1}{a_{ji}}, \tag{3}$$

and

$$a_{ii} = 1, \tag{4}$$

The matrix is consistent, if:

$$a_{ij} = \frac{w_i}{w_j}, \tag{5}$$

The matrix takes the following form [46,47]

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{6}$$

As a result of the comparison matrix's pairwise calculations, vectors of the priorities $w = (w_1, \ldots, w_n)$ concerning the importance of elements are obtained.

The priority vectors can be presented in the form of a normalized grade using the Saaty fundamental comparison scale [46,47]:

$$Aw = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_n \end{bmatrix} = n \times \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_n \end{bmatrix} \quad (7)$$

hence equality occurs [46,47]

$$Aw = nw, \quad (8)$$

In order to verify the consistency of the matrix, the principal eigenvalue λ_{max} corresponding to the highest value of the eigenvector should be determined in line using Equation (9) [46,47]:

$$\lambda_{\max} = \frac{1}{w_i} \sum_{j}^{n} a_{ij} w_j, \quad (9)$$

The pairwise comparisons matrix $A = (a_{ij})$ is consistent when its principal eigenvalue is close to n. In order to assess the accordance of deviations, a Consistency Index (CI) is determined using Equation (10) [46,47]:

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \quad (10)$$

Next, a Consistency Ratio (CR) is calculated, reflecting the extent to which the comparison of the validity of attributes is marked by incompatibility. This is given by [46,47]:

$$CR = \frac{CI}{RI}, \quad (11)$$

where RI is a Random Index that depends on the number of comparable items according to the matrix dimensions listed in Figure 7.

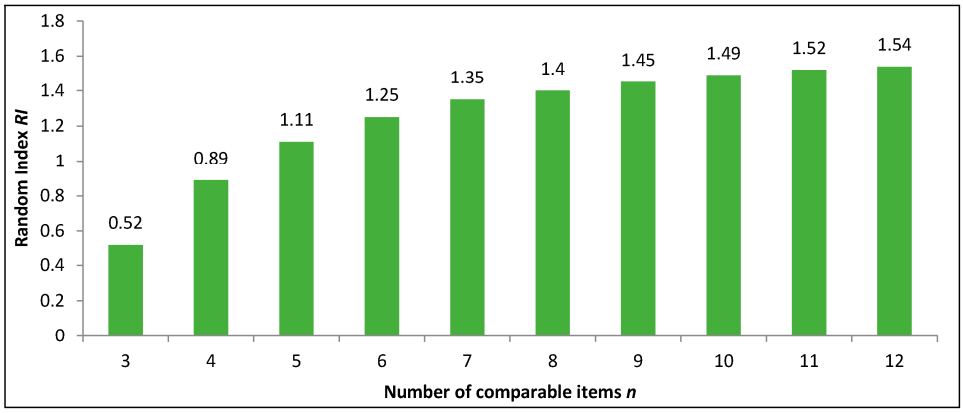


Figure 7. *RI* values corresponding to matrix dimensions (after Saaty [46,47]).

To calculate consistency indexes and weighting factors, in order to ensure that calculations performed were checked for their accuracy, methods using geometric and arithmetic means as well as matrix multiplication were used. Depending on the designated consistency ratio, preferential information can be accepted or rejected. If the value of CR is greater than the allowed 0.1, an inconsistent matrix is present and preferential information

should be verified. In such a case, actions will need to be taken to reduce the low-quality observations and the resultant inconsistencies.

Table 4 shows the categories and subcategories to assess the risk of failure of photovoltaic panels. The values for the criteria assessment subcategories are taken according to the severity of the failure, using a scale where low risk is 1, moderate risk is 2, and severe risk is 3.

Table 4. Evaluation criteria weights.

No.			Categories and Subcategories of Criteria		Point Weighting of Subcategories
1	1(a)	Design		Outdated building plans and blueprints, not taking into account renovations carried out, new chimneys, roofing replaced,	2
	1(b)			Failure to take into account the load-bearing capacity of the roof in the design of the photovoltaic installation,	3
	1(c)			Oversizing the inverter power,	2
	1(d)			Failure to consider shading from trees, chimneys or neighboring buildings,	3
2	2(a)	Performance		Installation company is certified and has the reference list, procedures related to the acceptance of investments, PV installation made with the latest technology,	1
	2(b)			Installation company has a reference list of completed investments, material verification and acceptance procedures are performed,	2
	2(c)			The company uses structures with safety certificates and approvals for assembly,	1
	2(d)			Use of high-quality photovoltaic panels and components,	1
3	3(a)	Operation	Frame damage	Fracture due to weight, e.g., of snow,	2
	3(b)			Depressurization,	3
	3(c)			Stratification,	3
	3(d)		Back cover failure	Yellowing,	1
	3(e)			Cracking,	2
	3(f)			Damage to electrical circuits,	2
	3(g)		Cell failures	Cracks in silicon,	1
	3(h)			Breaking the connections connecting the cells,	1
	3(i)			Increase in resistance and short circuit,	1
	3(j)		Shading of panels	Heating of shaded cells,	2
	3(k)			Installation performance drop,	2
	3(m)		Glazing of panels	Breakage of glass due to hail,	2
	3(n)			Water and oxygen entering the cell through the rupture,	2
	3(o)			Contamination of modules resulting in a decrease in power,	3
	3(p)		Junction box	Heating up,	1
	3(q)			Increase in contact resistance,	1
	3(s)			Wiring problems,	1
	3(t)		PV panels age	To 10 years,	1
	3(u)			From 10 to 20 years,	2
	3(v)			Above 20 years,	3
4	4(a)	Social	Nuisance resulting from building installation and green area	PV panel on ground,	1
	4(b)			PV panels on building,	2
5	5(a)	Financial	Size of possible losses when failure occurs	Financial loss of up to 10^2 EUR,	1
	5(b)			Financial loss from 10^2 to 10^3 EUR,	2
	5(c)			Financial loss above 10^3 EUR,	3
	5(d)		Difficulty of repair damage	Breakdown repair time up to 1 day,	1
	5(e)			Breakdown repair time from 1 to 7 days,	2
	5(f)			Breakdown repair time above 7 days,	3
6	6(a)	Environment	Annual average irradiance	To 800 kWh/m^2,	3
	6(b)			From 800 to 1000 kWh/m^2,	2
	6(c)			Above 1000 kWh/m^2.	1

The analysis was carried out for the six main criteria, which were compared in pairs according to the developed scale shown in Table 5.

Table 5. Matrix construction and weighting calculation for categories associated with failure risk assessment.

Category	1	2	3	4	5	6	Weight
1	1	2	2	2	4	5	0.320
2	0.5	1	2	2	4	5	0.252
3	0.5	0.5	1	2	3	5	0.190
4	0.5	0.5	0.5	1	2	2	0.120
5	0.25	0.25	0.333	0.5	1	2	0.070
6	0.2	0.2	0.20	0.5	0.5	1	0.048
Total	2.950	4.450	6.033	8	14.5	20	1.000

λ_{max} = 6.151; CI = 0.0302; RI = 1.25; CR = 0.0247.

As the determined CR is less than 0.1, the results obtained are acceptable. The preference vectors determined on this basis are shown in Table 6.

Table 6. A characterization of the PV panels.

No.		Categories and Subcategories of Criteria		Weight	
				Point Weight of Subcategories	Categories
1	1(a)	Design	Outdated building plans and blueprints, not taking into account renovations carried out, new chimneys, roofing replaced	2	0.320
	1(b)		Failure to take into account the load-bearing capacity of the roof in the design of the photovoltaic installation	3	0.320
	1(c)		Oversizing the inverter power	2	0.320
	1(d)		Failure to consider shading from trees, chimneys, or neighbouring buildings	3	0.320
2	2(a)	Performance	Installation company is certified and has the reference list, procedures related to the acceptance of investments, PV installation made with the latest technology,	1	0.252
	2(b)		Installation company has a reference list of completed investments, material verification and acceptance procedures are performed,	2	0.252
	2(c)		The company uses structures with safety certificates and approvals for assembly	1	0.252
	2d)		Use of high-quality photovoltaic panels and components	1	0.252
3	3(a)	Operation	Frame damage	Fracture due to weight, e.g., of snow	2	0.190
	3(b)			Depressurization	3	0.190
	3(c)			Stratification	3	0.190
	3(d)		Back cover failure	Yellowing	1	0.190
	3(e)			Cracking	2	0.190
	3(f)			Damage to electrical circuits	2	0.190
	3(g)		Cell failures	Cracks in silicon	1	0.190
	3(h)			Breaking the connections connecting the cells	1	0.190
	3(i)			Increase in resistance and short circuit	1	0.190
	3(j)		Shading of panels	Heating of shaded cells	2	0.190
	3(k)			Installation performance drop	2	0.190
	3(m)		Glazing of panels	Breakage of glass due to hail	2	0.190
	3(n)			Water and oxygen entering the cell through the rupture	2	0.190
	3(o)			Contamination of modules resulting in a decrease in power	3	0.190
	3(p)		Junction box	Heating up	1	0.190
	3(q)			Increase in contact resistance	1	0.190
	3(s)			Wiring problems	1	0.190
	3(t)		PV panels age	To 10 years	1	0.190
	3(u)			From 10 To 20 years	2	0.190
	3(v)			Above 20 years	3	0.190
4	4(a)	Social	Nuisance resulting from building installation and green area	PV panel on ground	1	0.120
	4(b)			PV panels on building	2	0.120
5	5(a)	Financial	Size of possible losses when a failure occurs	Financial loss of up to 10^2 EUR,	1	0.070
	5(b)			Financial loss from 10^2 to 10^3 EUR,	2	0.070
	5(c)			Financial loss above 10^3 EUR,	3	0.070
	5(d)		Difficulty of repair damage	Breakdown repair time up to 1 day	1	0.070
	5(e)			Breakdown repair time from 1 to 7 days	2	0.070
	5(f)			Breakdown repair time above 7 days	3	0.070
6	6(a)	Environment	Annual average irradiance	To 800 kWh/m^2	3	0.048
	6(b)			800–1000 kWh/m^2	2	0.048
	6(c)			Above 1000 kWh/m^2	1	0.048

The methodology used, due to its universality, can be applied to many photovoltaic installation configurations. The AHP method can be helpful, particularly for large photovoltaic farms. Thanks to this method, it is possible to support farm management processes by analyzing failures and weak points that are the reason for the reduced production of electricity and, consequently, the low profitability of the investment.

In fact, analysts working closer to designers, constructors, and operators of the PV installation were necessary to specify the categories and subcategories as listed in Table 4. The pertinent literature provided in the text served as the basis for the specification of the categories as well. Considering experts' opinions allows for taking into account all the key variables influencing the failure risk of PV installation.

All the key variables are influencing the risk values associated with PV installation failures.

The AHP method provides a scale comprising tolerable risk (6.89–8.27>, controlled risk (8.27–16.21> and unacceptable risk (16.21–20.67). The risk value $r(P)$ was calculated from Equation (1) is 12.79 and corresponds to the controlled risk category. This is due to the high probability of failures such as mechanical degradations. Mechanical degradations are mostly caused by hail and the difficulty in predicting the weather. The industrial can reduce the risk by selecting high-quality components designed and installed by highly qualified people and supported by the proper servicing of the installation.

5. Conclusions

The analysis shows that the largest number of publications on photovoltaic installation failures have been published by researchers from the USA. US researchers published 331 articles containing the analyzed keyword included in the Scopus database with a centrality index of 0.15. On the other hand, the publications written by scientists from Germany have the highest centrality index (0.20), which means that these studies on PV plant failure in Germany have the highest innovation and are the most frequently cited among scientists working on this topic. Furthermore, based on an analysis of the main interests of researchers, an increased interest in failure analysis using neural networks can be seen. With the use of citation burst, it can be assumed that further research into the use of neural networks will be carried out in the years to come.

The use of software such as CiteSpace makes it possible to analyze past and current trends in science. Software It is obvious that a detailed analysis of several thousand publications in a given field is practically impossible. Even the analysis capacity is rapidly increasing thanks to the extensive use of AI techniques and tools, which is the target of the Big Data Analysis field CiteSpace greatly facilitates the analysis of the literature and identifies the key issues facing scientists in a given field.

An analysis of the literature on the failure of photovoltaic installations has shown that failure monitoring and detection in real time are currently of greatest interest to researchers.

The main purpose of this manuscript is to present new approaches to the failure risk assessment of PV installations, as the obtained results support the management of PV, mainly in terms of strategic modernization plans and rehabilitation techniques. On the basis of the previously performed analysis through research on the failure rate (through performed bibliometric analysis), we propose a modified Multi-Criteria Decision Analysis with the implementation of the Analytic Hierarchy Process to perform a failure risk assessment.

The issue of assessing failure risk by combining different criteria of PV operation criteria remains to be developed. The authors want to emphasize the importance of the presented methodology for PV operators, which expect quick tools in the management process.

The development of photovoltaics represents an opportunity for enhancing national energy independence, which in the current geopolitical situation, is a strong argument for investing in renewable energy sources. The expected rapid demand for energy worldwide would give rise to serious consequences: energy shortage and unaffordable energy price. However, the development of distributed sources such as photovoltaic installations poses a serious problem for countries where the energy comes overwhelmingly from large coal-fired power plants and other hydraulic and fossil power plants. One example of such a

problem is the disconnection of inverters after an excessive voltage increase at the main grid. Consequently, the development of distributed sources requires the modernization of electricity grids. Therefore, it is important to analyze all aspects of photovoltaic installations, such as potential failures, using MCDA methods to better optimize the operational performance of such installations.

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References

1. Musial, W.; Ziolo, M.; Luty, L.; Musial, K. Energy Policy of European Union Member States in the Context of Renewable Energy Sources Development. *Energies* **2021**, *14*, 2864. [CrossRef]
2. Rabczak, S.; Nowak, K. Possibilities of Adapting a Free-Cooling System in an Existing Commercial Building. *Energies* **2022**, *15*, 3350. [CrossRef]
3. Karamov, D.N.; Ilyushin, P.V.; Suslov, K.V. Electrification of Rural Remote Areas Using Renewable Energy Sources: Literature Review. *Energies* **2022**, *15*, 5881. [CrossRef]
4. Kut, P.; Pietrucha-Urbanik, K.; Tchórzewska-Cieślak, B. Reliability-Oriented Design of a Solar-PV Deployments. *Energies* **2021**, *14*, 6535. [CrossRef]
5. Cergibozan, R. Renewable energy sources as a solution for energy security risk: Empirical evidence from OECD countries. *Renew. Energy* **2022**, *183*, 617–626. [CrossRef]
6. Serino, M.N. Energy security through diversification of non-hydro renewable energy sources in developing countries. *Energy Environ.* **2022**, *33*, 546–561. [CrossRef]
7. Rios-Ocampo, J.P.; Arango-Aramburo, S.; Larsen, E.R. Renewable energy penetration and energy security in electricity markets. *Int. J. Energy Res.* **2021**, *45*, 17767–17783. [CrossRef]
8. Trifonov, I.; Trukhan, D.; Koshlich, Y.; Prasolov, V.; Slusarczyk, B. Influence of the Share of Renewable Energy Sources on the Level of Energy Security in EECCA Countries. *Energies* **2021**, *14*, 903. [CrossRef]
9. Czekala, W.; Tarkowski, F.; Pochwatka, P. Social Aspects of Energy Production from Renewable Sources. *Eco-development Problems* **2021**, *16*, 61–66. [CrossRef]
10. Eurostat. Available online: https://ec.europa.eu/eurostat (accessed on 19 August 2022).
11. Paska, J.; Piotr, M. Modeling of photovoltaic power plants reliability. *Energy Market* **2014**, *111*, 81–86.
12. Lim, J.R.; Shin, W.G.; Lee, C.G.; Lee, Y.G.; Ju, Y.C.; Ko, S.W.; Kim, J.D.; Kang, G.H.; Hwang, H. A Study of the Electrical Output and Reliability Characteristics of the Crystalline Photovoltaic Module According to the Front Materials. *Energies* **2021**, *14*, 163. [CrossRef]
13. Maihulla, A.S.; Yusuf, I.; Salihu Isa, M. Reliability modeling and performance evaluation of solar photovoltaic system using Gumbel-Hougaard family copula. *Int. J. Qual. Reliab. Manag.* **2021**, *39*, 2041–2057. [CrossRef]
14. He, J.; Sangwongwanich, A.; Yang, Y.; Iannuzzo, F. Lifetime Evaluation of Three-Level Inverters for 1500-V Photovoltaic Systems. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *9*, 4285–4298. [CrossRef]
15. Dhimish, M.; Ahmad, A.; Tyrrell, A.M. Inequalities in photovoltaics modules reliability: From packaging to PV installation site. *Renew. Energy* **2022**, *192*, 805–814. [CrossRef]
16. Johnston, S.; Sulas-Kern, D.B.; Jordan, D. Photovoltaic Module Imaging for Hail Damage Assessment with Multi-year Follow Up. In Proceedings of the 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Fort Lauderdale, FL, USA, 25 April 2021; IEEE: New York, NY, USA, 2021; pp. 763–766.
17. Dubey, R.; Kottantharayil, A.; Shiradkar, N.; Vasi, J. Effect of Mechanical Loading Cycle Parameters on Crack Generation and Power Loss in PV Modules. In Proceedings of the 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Fort Lauderdale, FL, USA, 25 April 2021; IEEE: New York, NY, USA, 2021; pp. 799–802.
18. Yuan, S.; Yang, B.-F.; Zhang, J.-Y. Experimental study on short-circuit current characteristics of a photovoltaic system with low voltage ride through capability under a symmetrical fault. *Energy Rep.* **2022**, *8*, 4502–4511. [CrossRef]
19. Renaudineau, H.; Paradell-Sola, P.; Trilla, L.; Filba-Martinez, A.; Luis Dominguez-Garcia, J. Fault-Tolerant PV Multistring Inverter. In Proceedings of the 2021 13th Annual IEEE Green Technologies Conference Greentech 2021, Denver, CO, USA, 7–9 April 2021; IEEE: New York, NY, USA, 2021; pp. 75–80.
20. Esemen, M.; Gurler, S. Reliability based modeling of the performance of solar plants with multistate PV modules. *Hacet. J. Math. Stat.* **2022**, *51*, 606–617. [CrossRef]
21. Alves dos Santos, S.A.; Torres, J.P.N.; Fernandes, C.A.F.; Marques Lameirinhas, R.A. The impact of aging of solar cells on the performance of photovoltaic panels. *Energy Convers. Manag. X* **2021**, *10*, 100082. [CrossRef]

22. Yang, H.-Y.; Zhou, X.-D.; Yang, L.-Z.; Zhang, T.-L. Experimental Studies on the Flammability and Fire Hazards of Photovoltaic Modules. *Materials* **2015**, *8*, 4210–4225. [CrossRef]
23. Choudhary, M.; Shafiq, M.; Kiitam, I.; Hussain, A.; Palu, I.; Taklaja, P. A Review of Aging Models for Electrical Insulation in Power Cables. *Energies* **2022**, *15*, 3408. [CrossRef]
24. Rahman, M.M.; Hasanuzzaman, M.; Rahim, N.A. Effects of operational conditions on the energy efficiency of photovoltaic modules operating in Malaysia. *J. Clean. Prod.* **2017**, *143*, 912–924. [CrossRef]
25. Damianaki, K.; Christodoulou, C.A.; Kokalis, C.-C.A.; Kyritsis, A.; Ellinas, E.D.; Vita, V.; Gonos, I.F. Lightning Protection of Photovoltaic Systems: Computation of the Developed Potentials. *Appl. Sci.* **2021**, *11*, 337. [CrossRef]
26. Gobbo, S.; Ghiraldini, A.; Dramis, A.; Dal Ferro, N.; Morari, F. Estimation of Hail Damage Using Crop Models and Remote Sensing. *Remote Sens.* **2021**, *13*, 2655. [CrossRef]
27. Glavaš, H.; Žnidarec, M.; Šljivac, D.; Veić, N. Application of Infrared Thermography in an Adequate Reusability Analysis of Photovoltaic Modules Affected by Hail. *Appl. Sci.* **2022**, *12*, 745. [CrossRef]
28. Chrobak, P.; Skovajsa, J.; Zálešák, M. Effect of cloudiness on the production of electricity by photovoltaic panels. *MATEC Web Conf.* **2016**, *76*, 02010. [CrossRef]
29. Al-Taani, H.; Arabasi, S. Solar Irradiance Measurements Using Smart Devices: A Cost-Effective Technique for Estimation of Solar Irradiance for Sustainable Energy Systems. *Sustainability* **2018**, *10*, 508. [CrossRef]
30. Uematsu, Y.; Yambe, T.; Watanabe, T.; Ikeda, H. The Benefit of Horizontal Photovoltaic Panels in Reducing Wind Loads on a Membrane Roofing System on a Flat Roof. *Wind* **2021**, *1*, 44–62. [CrossRef]
31. Kuttybay, N.; Saymbetov, A.; Mekhilef, S.; Nurgaliyev, M.; Tukymbekov, D.; Dosymbetova, G.; Meiirkhanov, A.; Svanbayev, Y. Optimized Single-Axis Schedule Solar Tracker in Different Weather Conditions. *Energies* **2020**, *13*, 5226. [CrossRef]
32. Lebreton, C.; Kbidi, F.; Graillet, A.; Jegado, T.; Alicalapa, F.; Benne, M.; Damour, C. PV System Failures Diagnosis Based on Multiscale Dispersion Entropy. *Entropy* **2022**, *24*, 1311. [CrossRef]
33. Tavakoli, A.; Saha, S.; Arif, M.T.; Haque, M.E.; Mendis, N.; Oo, A.M.T. Impacts of Grid Integration of Solar PV and Electric Vehicle on Grid Stability, Power Quality and Energy Economics: A Review. *IET Energy Syst. Integr.* **2020**, *2*, 243–260. [CrossRef]
34. Hess, D.J. *Science Studies an Advanced Introduction*; Nyu Press: New York, NY, USA, 1997.
35. Che, S.; Kamphuis, P.; Zhang, S.; Zhao, X.; Kim, J.H. A Visualization Analysis of Crisis and Risk Communication Research Using CiteSpace. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2923. [CrossRef]
36. Hu, H.; Xue, W.; Jiang, P.; Li, Y. Bibliometric analysis for ocean renewable energy: An comprehensive review for hotspots, frontiers, and emerging trends. *Renew. Sust. Energ. Rev.* **2022**, *167*, 112739. [CrossRef]
37. Yang, Z.; Huang, D.; Zhao, Y.; Wang, W. A Bibliometric Review of Energy Related International Investment Based on an Evolutionary Perspective. *Energies* **2022**, *15*, 3435. [CrossRef]
38. Guo, Y.; Geng, X.; Chen, D.; Chen, Y. Sustainable Building Design Development Knowledge Map: A Visual Analysis Using CiteSpace. *Buildings* **2022**, *12*, 969. [CrossRef]
39. Wang, D.; Huangfu, Y.; Dong, Z.; Dong, Y. Research Hotspots and Evolution Trends of Carbon Neutrality-Visual Analysis of Bibliometrics Based on CiteSpace. *Sustainability* **2022**, *14*, 1078. [CrossRef]
40. Liu, C.; Yuan, Y.; Zhou, A.; Guo, L.; Zhang, H.; Liu, X. Development Trends and Research Frontiers of Preferential Flow in Soil Based on CiteSpace. *Water* **2022**, *14*, 3036. [CrossRef]
41. Liu, Z.; Yin, Y.; Liu, W.; Dunford, M. Visualizing the intellectual structure and evolution of innovation systems research: A bibliometric analysis. *Scientometrics* **2015**, *103*, 135–158. [CrossRef]
42. CiteSpce. Available online: https://citespace.podia.com/ (accessed on 19 August 2022).
43. Chine, W.; Mellit, A.; Lughi, V.; Malek, A.; Sulligoi, G.; Massi Pavan, A. A novel fault diagnosis technique for photovoltaic systems based on artificial neural networks. *Renew. Energy* **2016**, *90*, 501–512. [CrossRef]
44. Alam, M.K.; Khan, F.; Johnson, J.; Flicker, J. A Comprehensive Review of Catastrophic Faults in PV Arrays: Types, Detection, and Mitigation Techniques. *IEEE J. Photovolt.* **2015**, *5*, 982–997. [CrossRef]
45. Ali, M.H.; Rabhi, A.; Hajjaji, A.E.; Tina, G.M. Real Time Fault Detection in Photovoltaic Systems. *Energy Procedia* **2017**, *111*, 914–923. [CrossRef]
46. Saaty, T.L. A scaling method for priorities in hierarchical structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]
47. Saaty, R.W. The analytic hierarchy process—What it is and how it is used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
48. Pietrucha-Urbanik, K.; Tchórzewska-Cieślak, B. Approaches to Failure Risk Analysis of the Water Distribution Network with Regard to the Safety of Consumers. *Water* **2018**, *10*, 1679. [CrossRef]