

Protection Against Direct Atmospheric Discharges and Overvoltages in Photovoltaic Installations

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Abstract – The increasing global energy demand has led to the expansion of photovoltaic (PV) power plants, particularly in response to climate goals like the European Union's "Fit for 55" initiative to reduce CO₂ emissions by 55% by 2030. However, as PV installations grow, their vulnerability to atmospheric discharges, such as lightning, also increases. This study investigates the design and dimensioning of lightning protection systems for PV plants, focusing on two methods: traditional protection per IEC 62305 standards and ionizing devices based on NP 4426 standards. Both methods were analyzed for technical feasibility and cost-effectiveness. A case study of the PV installations at the Lisbon Engineering School (ISEL) was conducted, and a risk analysis determined that Level III protection was required. The study demonstrated that both methods provide effective protection, but ionizing devices offer a more cost-efficient solution, with lower material and labor costs. Consequently, the study showed that ionizing method is around 35% affordable than traditional rods for protecting PV plants in urban environment against atmospheric discharges.

Keywords—*photovoltaic, risk, atmospheric discharges, protection*

I. INTRODUCTION

While photovoltaic (PV) systems are widely acknowledged as essential to achieving renewable energy targets, particularly within the framework of the EU's "Fit for 55" initiative, certain critical areas of research remain underexplored. Specifically, the vulnerability of PV installations to atmospheric discharges and the effectiveness of current protective measures needs further investigation. Although standards like IEC 62305 [1] and NP 4426 [2] offer guidelines for lightning protection, there are gaps in understanding how these protective measures perform under varying environmental conditions and in different PV plant configurations. Authors in [3] presented and discussed dynamic lightning protection of microgrid. Due to exposure PV systems may not be properly protected against lightning., they may suffer an impact in a way that can lead towards severe damage, such as, failures in building electrical and electronic equipment and or induce the PV panels disruption and anormal operation [4, 5]. This kind of destruction will certainly affect the economic aspects regarding the PV power generation, adding also the repair or replacement cost, all of which can be mitigated by implementing a lightning protection system (LPS) [6, 7].

In [8] it was assessed surges due to lightning strikes and the required protection measures based on the results of risk analysis and protection costs additionally, the lack of comprehensive risk assessments that integrate human safety, economic viability, and material protection in diverse geographic and meteorological contexts hinders the development of optimized protection systems. Another underexplored area is the impact of lightning on the newer types of PV materials and system configurations. A comprehensive review of the superior modeling methods of PV systems during lightning strikes were presented in [9].

Most current research focuses on traditional PV panels, but as the technology evolves, it is necessary to study how newer materials and components react to both direct and indirect atmospheric discharges, or how to prevent the systems from dangerous faults such as surges, lighting and grounding [10-12]. Another, studies present methodologies for assessing risk of lightning damage and determining protection requirements and explore different protection measures to enhance their resilience [13, 14].

One significant gap is the economic feasibility of different lightning protection solutions, particularly for utility-scale PV plants and self-consumption units. While the ionizing device method has been proposed as a cost-effective alternative to traditional lightning rods, comparative studies on their long-term effectiveness and maintenance requirements are limited.

Furthermore, the integration of smart monitoring systems that can provide real-time protection and response to lightning events is still in its infancy, offering a promising direction for future research. This paper aims to address these gaps by providing a comprehensive risk assessment for PV systems and exploring the cost-effectiveness of advanced lightning protection technologies in different environmental settings.

II. PHOTOVOLTAIC PLANTS – INTRODUCTION

Photovoltaic plants can be differentiated into two main types: Utility Scale Plants and Self Consumption Production Units. The basics are similar for both types, with the only difference being the way they are connected to the grid.

Large-scale plants, as the name implies, have a larger grid injection capacity. As a result, the implementation area is larger. Self-consumption power plants are usually smaller in size. They can be used in industrial buildings or for residential use. In this specific case, the meter must be

bidirectional so that the energy can be properly catalogued. The basic components of a photovoltaic plant are shown below:

1. Photovoltaic panels;
2. Solar cables (DC);
3. Distribution cables (AC);
4. Inverters;
5. Transformer;
6. Substation (Utility Scale).

Photovoltaic panels (1.) are connected in series to form what is known as a string, and the number of panels in each string can be adjusted to meet specific needs. These panels can vary significantly based on the make and model, each offering unique features and performance characteristics. This variety allows for customized configurations to optimize energy output.

The energy generated by the panels, in direct current (DC), is transmitted to the inverter through solar cables (2.). The inverter (4.) then plays a crucial role, converting the DC energy into alternating current (AC) for practical use. The voltage produced by the inverter can differ depending on the model, but typically ranges between 600V and 800V.

Inverters have a fundamental characteristic: they are either on-grid or off-grid. On-grid inverters are used when the power plant is connected to the RESP (public service electrical grid) at whatever voltage level. Off-grid inverters, on the other hand, cannot be used when a connection is made to the RESP. This type of inverter is used in self-consumption units, that are not connected to the external grid. In Fig.1 and Fig.2, it can be seen the connection diagram for an off-grid and on-grid inverter, respectively.

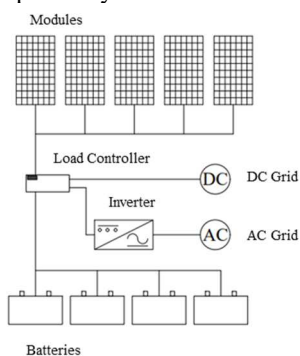


Fig. 1. Inverter off-grid

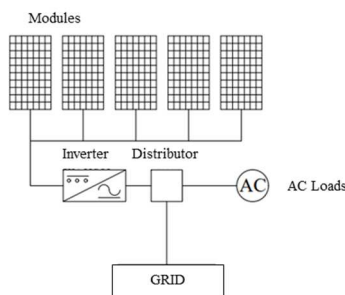


Fig. 2. Inverter on-grid

If the photovoltaic plant is a self-consumption production unit, the inverter connects to the AC loads, via AC cable and the border line is the electrical panel where the cable is connected to. In the case of a utility scale PV plant, there are still two more items in the list, the transformer and substation.

In the case of a UPP (Portuguese for Small Production Unit), where the maximum injection power is 0.99MVA, there is no need for a substation. However, each UPP requires

a step-up transformer, with a transformation ratio smaller than one. The purpose of the transformer is to transform low voltage (0 to 1000V) into medium voltage (1kV to 35kV) and the voltage at the secondary of the transformer is usually 10kV, 15kV or 30kV. A PV plant can have more than one UPP, so more than one transformer, and the power of the various transformers is joined together at the sectioning station. This sectioning station is built by the developer of the PV plant, but it becomes the domain of RESP as soon as it is completed. This is where the energy is delivered for sale, so this is where the metering mechanisms are present.

In the case of a park with a very high injection power, this is not the case. In cases where the energy is delivered in High Voltage (HV), a substation is required. The purpose of the substation is to raise the voltage from medium voltage to high voltage so that it can then make its way to the RESP infrastructure.

III. ATMOSPHERIC DISCHARGES

A. Introduction to atmospheric discharges

In the past, the atmospheric discharges were always treated as a danger to living beings or even a fire hazard. Nowadays, with the advance of technology and the increase in semiconductor devices that work with weak currents, i.e. currents with a lower instantaneous value, the danger of lightning strikes has been extended to them. Atmospheric discharges are discharges in the form of electrical energy, of great size and intensity, but with a very short duration. They can be several kilometers long and reach thousands of Amperes. They can reach temperatures of more than 3000 degrees Celsius [15]. This heating gives the name to the phenomenon known as lightning, causing a bright "path" with a loud sound effect.

The electrical nature of atmospheric discharges goes back to 1752, through Benjamin Franklin, in his famous "kite" experiment. In this experiment, Franklin used a kite with a metal rod and, on a rainy day, launched the kite to prove that lightning strikes occur naturally. This experiment led to the invention of the well-known lightning rod.

Lightning strikes can be caused by volcanic eruptions, extremely intense forest fires and snow or even dust storms. However, most lightning strikes occur in storm clouds, or thunderclouds. For lightning to occur, a given region of the atmosphere must be electrically charged. The discharge begins when the electric field produced by the charges present in the atmosphere exceeds the insulating capacity, or dielectric strength, of the air. This results in an extremely rapid movement of electrons from a negatively charged region to a positively charged one. The discharge can hit any type of object on the ground, such as trees, cars, buildings or even people.

Atmospheric Electrical Discharges can be classified as:

- Cloud to Ground;
- Between the Cloud;
- Cloud to Cloud;
- Cloud to Air.

The most common type of lightning strike is the first one mentioned, i.e. cloud-to-ground (in particular negative charges from the cloud descend to the ground), that is also the most danger to society, ranging from the ignition of fires to the death of living beings. When it comes to creating an

atmospheric discharge from the cloud to the ground, there can be 4 types [15] as can be seen in Fig. 3:

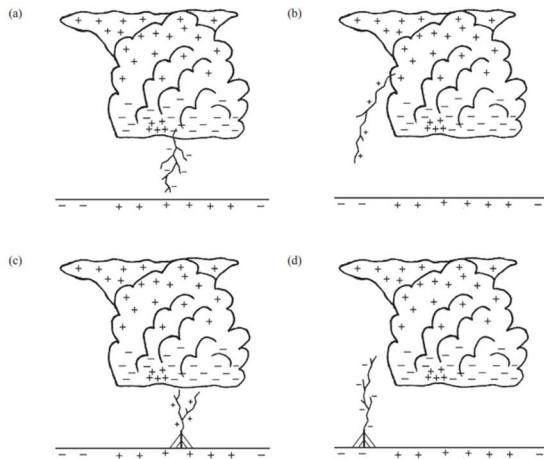


Fig. 3. a) Negative charges from the cloud descend to the ground; b) Positive charges from the cloud descend to the ground; c) Negative charges from the ground ascend to the cloud; d) Positive charges from the ground ascend to the cloud.

The striking distance or lightning return stroke is defined by the lighting current magnitude with the rolling sphere as (1) [16] as follows:

$$i(0, t) = \frac{i_0}{\eta} \times \frac{\left(\frac{t}{t_1}\right)^n}{1 + \left(\frac{t}{t_1}\right)^n} \exp\left(\frac{-t}{t_2}\right) \quad (1)$$

where i_0 is the lighting current magnitude, t_1 is the front time of the lightning strike, t_2 is the decay time of the lightning and n is the exponent value (2–10), which is expressed by (2) [16]:

$$\eta = \exp\left[-\left(\frac{t_1}{t_2}\right) \times \left(n \times \frac{t_2}{t_1}\right)^{\frac{1}{n}}\right] \quad (2)$$

B. Atmospheric discharges consequences

1) In people

When lightning strikes the ground, it creates a phenomenon known as step voltage, where an induced voltage varies with distance from the impact point. This can be dangerous for living beings, as the difference in voltage between their feet can generate a current through their body, potentially causing electrification or electrocution. Direct lightning strikes can result in severe injury or death, with an estimated 2,000 fatalities each year due to lightning, according to [17].

2) In PV plants

Photovoltaic plants are highly exposed to all kinds of meteorological hazards, with lightning strikes being one of the worst, if not the worst, of them all. The fact that they are mounted either on top of buildings or even on the ground, and that they have a very large area, means that this level of danger is high. These factors lead to a high probability of direct atmospheric discharges, causing electrical, thermal, and mechanical problems. It should be noted that around 26% of all problems in photovoltaic plants are caused by lightning and atmospheric discharges [9].

When lightning strikes an energy-producing photovoltaic plant, high currents will flow through all the conductive parts of the plant and consequently high voltages will also be induced in the components, which could deteriorate the material present in the plant, causing it to have a shorter lifespan and the plant to lose profitability [18].

III. PREVENTION AGAINST ATMOSPHERIC DISCHARGES

A. Direct Discharges

There is a fundamental standard for protection against atmospheric discharges, IEC 62305 [1], was created in September 2006 to replace the older standard, 6651:1999. For a short time, both standards governed at the same time, but from August 2008 IEC 62305 has been acting alone. The standard currently in use has a greater scientific understanding of lightning and its effects over the last 20 years. What's more, it evaluates the growth of technology and electronic systems that are increasingly present in our daily lives. The IEC 62305 standard is divided into four parts, General Principles, Risk Management, Physical Damage to Structures and Human Risks and Protection of Electronic Systems. For the design/placement of a LPS system, Fig. 4, three different methods can be used:

- Rolling sphere method (sphere radius, R , depend from the chosen risk level);
- Protection angle method (angle, α , depend from the chosen risk level);
- Mesh method (mesh distance depend from the chosen risk level).

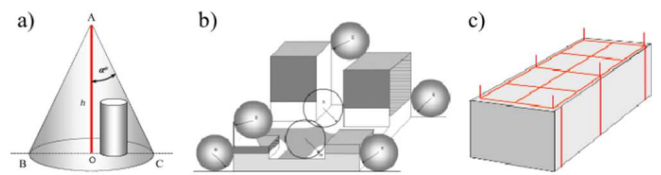


Fig. 4. Protection design methods according to IEC 62305:2010 [19]: a) Protection angle method, b) rolling sphere method, and c) mesh method.

The rolling sphere radius, is given by (3),

$$r = 10 \times I^{0.65} \quad (3)$$

where I is the maximum peak value of the lightning current [1] that is defined for the several LPS class levels, therefore, the sphere radius and mesh size are also established and shown in Table 1, and the protection angle in Fig. 5.

TABLE I. PROTECTION METHOD [1]

Class of LPS	Rolling sphere Radius, r (m)	Mesh size (m)
I	20	5×5
II	30	10×10
III	45	15×15
IV	60	20×20

In a LPS with traditional lightning rod (Franklin tip), the action is passive. In other words, the lightning is formed naturally and the lightning rod, together with the other components of the LPS, only receives and directs the electrical discharge to the ground in a safe manner.

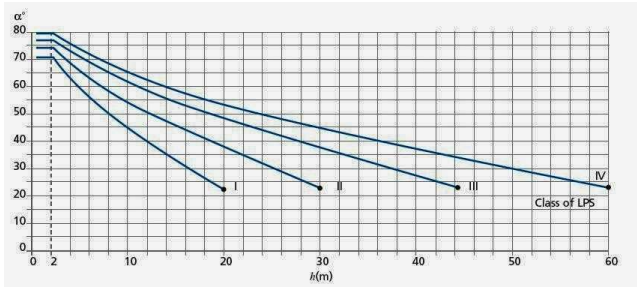


Fig. 5. Protection angle calculation.

Another fundamental standard for protection against atmospheric electrical discharges is NP 4426 of 2013 - Protection systems with non-radioactive ionization devices that applies to the protection of any structure against direct lightning strikes using a non-radioactive ionization device. Lightning protection ionization rod devices, commonly referred “early streamer emission” (ESE) lightning rods, unlike conventional rods, which passively wait for a strike, ESE devices actively seek to intercept and channel the strike safely into the ground by using advanced ionization techniques. There has been ongoing debate regarding the actual efficacy of ESE rods. Some studies [20, 21] argue that the time-advancement effect is minimal, and the performance improvement over traditional systems may not be as significant in real-world conditions. Different countries have varying standards for lightning protection, and not all of them recognize or endorse ESE technology. For example, the International Electrotechnical Commission (IEC) standard (IEC 62305) does not formally recognize ESE systems, whereas French standards (NF C 17-102) [22] do.

The ionization principle is related with the time when a storm cloud forms, and the electrical charges start to accumulate, then, the device triggers controlled ionization by emitting a stream of ions (positive or negative) into the surrounding air. The ESE are validated by laboratories and its effectiveness is given by ΔT in microseconds, being the maximum value allowed $60\mu s$ [2]. Thus, ESE has a more complex protection radius when compared with the traditional ones. The following equation (4) [2] shows the behavior of the protection radius.

$$\begin{cases} R_p(h) = \sqrt{2rh - h^2 + \Delta(2r + \Delta)}, \text{ for } h \geq 5m \\ R_p(h) = \frac{(h \times R_p(5))}{5}, \text{ for } 2m \leq h < 5m \end{cases} \quad (4)$$

Where:

- $R_p(h)$ [m] \rightarrow protection radius at a height of h ;
- h [m] \rightarrow height of the vertex in relation to the highest horizontal plane to be protected;
- r [m] \rightarrow radius of the rolling dummy sphere, depending on the LPS class (consult Table I);
- $\Delta = \Delta T \times 10^6$.

Once the equation is in place, it can be plotted the evolution of the protection radius as a function of the height of the rod. This was done to get a better understanding and visual perception of the equation's behavior.

Fig. 6 illustrate an ESE application on a building.

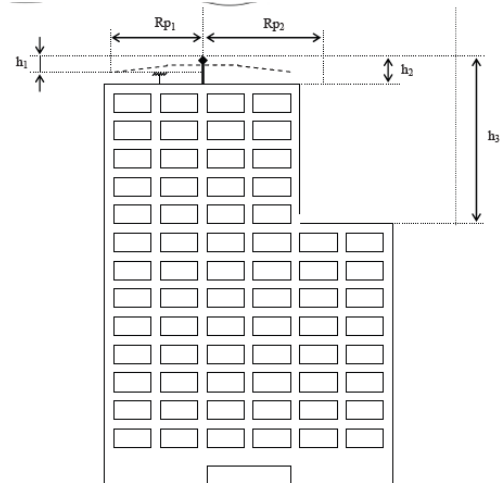


Fig. 6. ESE application example.

IV. CASE STUDY CHARACTERIZATION

The case study of this document is the photovoltaic installation at ISEL. ISEL dates back to the reign of King Maria II, more specifically to 1852, when it was founded under the name of the Lisbon Industrial Institute. Only in December 1974, after the revolution, did it take on the name it still has today, and only in 1988 did it become part of the Polytechnic Institute of Lisbon, Fig. 7.

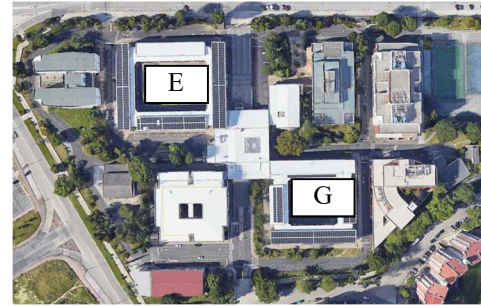


Fig. 7. ISEL campus (38.75691186259142, -9.116494150002076)

Two building E and G, have photovoltaic panels installation. This photovoltaic installation solution for self-has a total of 1356 modules, 789 in building E and 564 are in G. The lightning protection system implementation can be done in various ways, depending on the purpose, the designer or available budget. In this study, the methodology used had the following steps:

1. Risk calculation for ISEL buildings using IEC 32305-2;
2. Develop a 3D model of the ISEL buildings and panels;
3. Use the 3D model in an electrogeometric software to be aware of the vulnerability points;
4. Define several scenarios with the traditional vertical rods (height, location, protection angles, etc.) and the same procedure with de ESE rods;
5. Design the protection mesh that will interconnect the rods regarding point 3, the down conductors and the earth electrodes.
6. Technical and economic analysis of the developed solutions.

For an accurate class level chose of a lightning protection system, a risk analysis can be carried out [1, 23]. Three types of risk are considered in the risk analysis, Loss of human life

(R1), Loss of public service (R2) Loss of cultural heritage (R3). For this study, the risk of loss of cultural heritage will not be taken into account since ISEL's photovoltaic installations are not included. For the 3 mentioned risks above there are values considered to be tolerable risk values, $R_1=10^5$ (risk of 1 in 100 000), $R_2=10^{-3}$ (risk of 1 in 1000) and $R_3=10^{-4}$ (risk of 1 in 10 000).

After analyzing all the risk parameters, the adequate class level III. Therefore, all the dimensioning of the lightning protection systems must follow the assumptions of both the IEC 62305 and NP 4426 for LPS class III. Using AutoCAD software and the electrogeometric method and respecting international standards, was carried out on the buildings in which photovoltaic systems are installed, Fig. 8 and Fig. 9. The entire area covered the photovoltaic installation on both buildings is completely exposed, and it was yellow marked in all vulnerable points, for LPS class level 1 to 4, meaning that the entire area must have to be protected against lightning strikes.

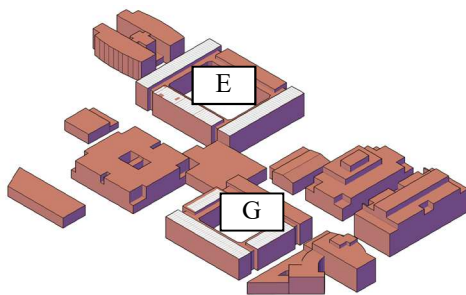


Fig. 8. 3D panels implementation

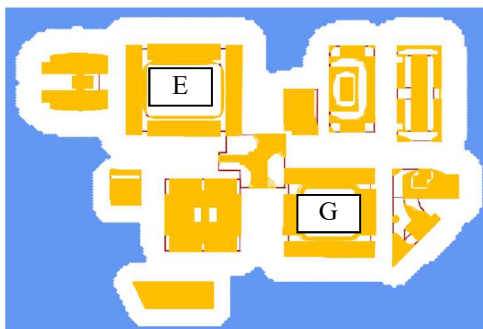


Fig. 9. Vulnerability analysis Level III.

Two different solutions were adopted for dimensioning the protection. Solution 1 is through the traditional method exemplified in IEC 62305, and solution 2 is through the ionizing devices mentioned in NP 44226. Fig. 10 and Fig. 11, illustrate the developed 3D models for traditional rods end ESE respectively.

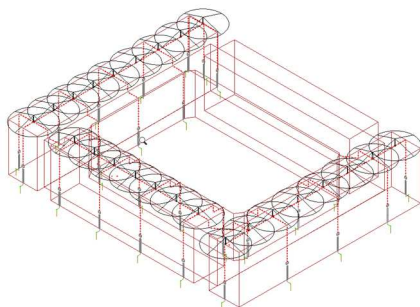


Fig. 10. 3D traditional vertical rods implementation building E example.

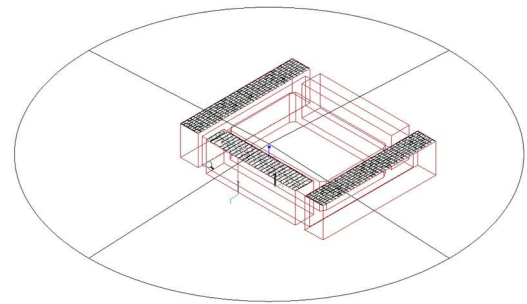


Fig. 11. 3D ESE vertical rod implementation in building E example.

As expected, the traditional method needs many rods (depending from the height), and in our study only one ESE is needed. In addition, the equipotentialisation of all the panels and metal parts present in the photovoltaic installation has been dimensioned, requiring them to be earthed.

It should be noted that at this point any solution is valid, since it ensures 100 per cent protection of the entire photovoltaic installation. What is missing is an economic analysis of the purchase of materials and labor to carry out the project, as will follow next. The four different scenarios presented in Table II will result in two different budgets, as in materials, or manpower. One budget for the traditional method and one for the ionizing devices.

TABLE II. DFERENT SCENARIOS

Scenarios	
Building E - traditional method	
Building E - ionizing devices	
Building G - traditional method	
Building G - ionizing devices	

Both the budgets will be presented in Table III and IV, respectively.

TABLE III. BUDGET FOR THE TRADITIONAL METHOD

Traditional Method	
Building E	42 950,01 €
Building G	34 724,83 €
Building E - Equipot	20 224,00 €
Building G - Equipot	15 360,00 €
Total	113 258,84 €

TABLE IV. BUDGET FOR THE IONIZING DEVICES

Ionizing Devices	
Building E	3 143,01 €
Building G	2 926,77 €
Building E - Equipot	20 224,00 €
Building G - Equipot	15 360,00 €
Total	41 653,78 €

Observing Table III and IV, and comparing them, the traditional method has a much higher monetary value than the ionization method. Adding the labor cost to the material, it was estimated that this would be around 30% of the cost of the material. With this increase, the final values are presented in Table V.

TABLE V. FINAL BUDGET

Final Budget	
traditional method	147 236,49 €
ionizing devices	54 149,91 €

In percentage terms, the option of solution 2, protection by ionizing method, is calculated as follows (5):

$$\%_{dif} = \left(1 - \left(\frac{Value_{trad}}{Value_{ion}}\right)\right) \times 100 \quad (5)$$

$$\Leftrightarrow \left(1 - \frac{147\,236,49}{57\,149,91}\right) \times 100 = 63,2\%$$

Therefore, since the option of protection through ionizing devices ensures complete protection of the photovoltaic system, with less material and labor cost, it reveals to be the right implementation choice.

V. CONCLUSIONS

The study highlights important findings related to photovoltaic (PV) plants and the need for protection from atmospheric discharges, particularly lightning strikes. The expansion of PV plants, driven by environmental goals such as the EU's "Fit for 55," shows the growing importance of solar energy in reducing carbon emissions. Both large-scale and self-consumption PV systems are vital in diversifying energy sources and reducing reliance on fossil fuels.

PV plants are especially vulnerable to lightning due to their outdoor exposure, which poses risks to both equipment and safety. Lightning strikes, whether direct or indirect, can cause significant electrical, thermal, and mechanical damage, ultimately shortening the operational lifespan and profitability of these plants. To address this, protection against atmospheric discharges must comply with standards like IEC 62305 and NP 4426, which outline guidelines for protecting structures and electronic systems. A comprehensive risk assessment is essential, considering human safety, public service reliability, and material protection.

The study evaluates two lightning protection methods—traditional lightning rods and ionizing devices—and concludes that ionizing devices offer equally effective protection at a lower cost, both in materials and labor. This makes ionizing devices the preferred choice for PV installations.

The rapid growth of PV plants emphasizes the importance of implementing effective risk management systems to protect against environmental hazards. The adoption of cost-effective lightning protection methods will help ensure the longevity and safety of renewable energy infrastructure, contributing to energy security and sustainability. The budget for the solution using ionizing devices is around 63,2% cheaper, making it the right choice for implementation.

Looking forward, future research could focus on optimizing lightning protection strategies for larger and more complex PV systems, particularly in diverse environmental conditions.

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