This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

A Methodology for Protection of Trees Against Lightning Strikes as a Measure to Prevent Fires and Loss of Human Life

Massimo Mitolo
Fellow, IEEE
Irvine Valley College Electrical Department
5500 Irvine Center Drive, Irvine, CA 92618, USA
mitolo@ieee.org

Enrico Pons
Member, IEEE
Politecnico di Torino
Dipartimento Energia "G. Ferraris"
Corso Duca degli Abbruzzi 24
Torino, Italy
enrico.pons@polto.it

Gaetano Zizzo
Senior Member, IEEE
Università di Palermo
Department of Engineering
Viale delle Scienze, Edificio 9
Palermo, Italy
gaetano.zizzo@ieee.org

***Abstract*-- Some regions may be characterized by a very low annual lightning ground flash density, and yet lightning strikes seem to have been in those areas the cause of widespread wildfires in forested areas. Due to global climate change, these occurrences seem to be an increasing threat.**

In this paper, the authors discuss the withstand capability of trees against lightning and introduce the criteria for the deployment of tree lightning protection systems (TLPS) to protect forested areas, where deemed necessary by the tree risk assessment. This work analytically identifies the critical trunk radius of the tree below which the tree may explode in the case of a lightning strike and ignite the surrounding vegetation.

The critical heights of trees requiring lightning protection systems to prevent loss of human life and cultural heritage are also identified.

***Index Terms*-- collection area, flash density, form factor, lightning, resistivity, trees, wood density, wood resistivity.**

I. Introduction

Lightning strikes have been the catalyst of massive uncontrolled fires in areas of combustible vegetation. In some regions, lightning strikes may be a relatively unusual occurrence (e.g., California), but instead, they seem to have become a major contributor to the propagation of wildfires, as a by-product of climate change. Given such unusual weather, fires originating from lightning are an increasing threat.

Reference [1] projects that the number of lightning-ignited fires will increase by 19.1% by 2020 to 2049 and the annual area burned at high severity will increase by 21.9%. These projections depict a scenario where climate-induced bushfires may become a serious threat to persons and assets.

In the landscape, tall trees are the most receptive elements of lightning strikes, especially those growing on hills. Lightning striking a tree causes the circulation of an intense electrical current, which flows to the ground through the trunk and the roots. The tree can catch on fire, and so can the neighboring vegetation, with the risk of initiating a spreading catastrophic wildfire.

A proactive approach to prevent the ignition of forested areas and mitigate the propagation of wildfires may be the deployment of lightning protection systems (LPS) to protect:

1. trees that are deemed likely to be hit by lightning per applicable standards, and
2. trees that are deemed likely to explode and splinter, and present a fire hazard to the surrounding, based on their physical characteristics.

Trees may not necessarily belong to both categories.

This approach would involve the installation of air terminals, possibly integrated in trees, connected to grounding systems via down conductors.

The authors believe that the above strategy would prevent the ignition of trees by allowing the safe discharge to the ground of the energy from these more often occurring lightning strikes, and therefore decrease the risk of wildfire.

While the authors understand that this solution may be expensive for wide deployment, they also believe that the cost would pale in juxtaposition to the life, economic, and environmental price associated with wildfires.

The paper is structured as it follows:

- Section II discusses the withstand capability of a tree, proposing a method for calculating the minimum cross-sectional area *S* of the trunk that allows a tree to withstand the lightning current without posing a fire hazard to the surroundings.
- Section III provide a method for calculating the equivalent collection area of a tree, introducing a form factor to include different shapes of trees in equivalent collection area calculations;
- Section IV proposes the methodology for assessing the risk of direct flashes to trees considering both the risk of loss of human life and the risk of loss of cultural heritage. The methodology is partly based on the probabilistic approach proposed by the internationally recognized technical standard IEC 62305 [2], which is considered one of the most complete approach for the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

lightning risk assessment [3] [4];

- Section V proposes the calculation of the critical heights of trees requiring lightning protection systems in both best-case and worst-case scenarios.

II. Withstand Capability of a Tree

During a lightning discharge, the thermal energy W generated within the trunk is the product of its resistance R and the specific energy of the lightning flash conveyed by the lightning current i (1).

$$W = R \int i^2 dt \tag{1}$$

The lightning current has a very brief duration, therefore the thermal exchange by convection or radiation between the tree and the environment is not significant. The phenomenon is therefore adiabatic, and the heat trapped in the trunk will raise its temperature.

If the trunk has a cross-sectional area large enough to avoid the superheating of the moisture within the tree, which could cause splintering and the projection of hot sharp wood fragments, likely to cause a fire hazard to the surroundings, lightning-induced wildfires may be avoided.

Critical cross-sectional areas of the trunk can be obtained by equating the thermal energy generated by the lightning to the heat accumulated within the trunk, which depends on the makeup of the wood and the trunk's physical size.

Thus, the minimum cross-sectional area S (in m^2) of the trunk that allows the tree to withstand the lightning current without posing a fire hazard to the surroundings, is given by (2) [2] [5] [6].

$$S = \sqrt{\frac{\frac{W}{R}\rho\cdot\alpha}{\gamma\cdot c\cdot \ln[\alpha\cdot(T_M - T_0)+1]}} \tag{2}$$

where:

- W/R is the specific energy of the current impulse (J/Ω). It represents the energy dissipated by the lightning current per unit of resistance;
- ρ is the electric resistivity of the wood at 20°C (Ωm);
- α is the temperature coefficient of resistance of wood (1/K);
- γ is the wood density (kg/m^3);
- c is the wood thermal capacity (J·kg^{-1}·K^{-1});
- T_M is the critical temperature that the trunk could reach after the expiration of the lightning current, which poses a fire hazard to the surroundings, 523 K (250°C) [5];
- T_0 is the wood temperature before the lightning strike, herein 293 K (20°C).

A. Resistivity and temperature coefficient of resistance α

Dry wood is an exceptional electrical insulator, with a resistivity of about 10^{15} - 10^{16} Ω·m at ambient temperature. However, the resistivity dramatically decreases as the moisture content of the wood increases. For a tree at fiber saturation, the resistivity becomes 10^3-10^4 Ω·m [8]-[9]. The fiber saturation denotes the point at which wood cannot absorb any more water (i.e., 30% moisture content). In this condition, the trunk exhibits a conductive behavior that may be characterized by a value α of 0.004 K^{-1} (typical of conductors).

B. Wood density γ

For wood, both mass and volume depend on moisture content, therefore, the wood density γ to be used in (1), at a given percentage moisture content m, may be determined with (3) [7].

$$\gamma = 1{,}000 \cdot G \cdot \left(1 + \frac{m}{100}\right) \tag{3}$$

G is the specific gravity of wood, defined as the ratio of the density of dry wood to the density of water at a specified reference temperature, typically 4°C, where the density of water is 1,000 kg·m^{-3} [7].

The specific gravity G ranges between 0.3 and 0.7, depending on the type of tree (e.g., White Ash). Thus, at fiber saturation, γ ranges between 390 kg·m^{-3} and 910 kg·m^{-3}.

C. Wood thermal capacity

The wood thermal capacity c is defined as the amount of energy necessary to increase one unit of mass (in kg) by one unit in temperature (in K).

c does depend on the temperature and moisture content of the wood but is virtually independent of its density or type and can be calculated with equations (4) [7].

$$c = \frac{c_0 + 0.01\cdot m\cdot c_{h20}}{1+0.01\cdot m} + A, \tag{4}$$

where:

$$A = -619.1\cdot10^{-4}\cdot m + 2.36\cdot10^{-4}\cdot m\cdot T - 1.3\cdot10^{-4}\cdot m^2 \tag{5}$$

$$c_0 = 0.1031 + 0.003867\cdot T \tag{6}$$

m is the moisture content, which is assumed at fiber saturation (i.e., 30%); T is the wood temperature (K); c_0 is the thermal capacity of dry wood, which is 1.24 kJ·kg^{-1}·K^{-1} at T =

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

293 K (20°C); c_{h20} is the thermal capacity of water (4.18 kJ·kg^{-1}·K^{-1}). In the above conditions, the wood thermal capacity c is about 2 kJ·kg^{-1}K^{-1}.

D. *Specific energy of the current impulse*

Reference [10] tabulates values of lightning current parameters and lists the cumulative frequency distribution of the specific energy *W/R* (Table I).

TABLE I
TABULATED VALUES OF *W/R*

	***W/R* (kJ/Ω)**		
Type of stroke	**95%**	**50%**	**5%**
First negative stroke	6	55	550
First positive stroke	25	650	15,000

To determine the values of the trunk radius below which the tree will sustain damage and may catch on fire, equation (2) has been evaluated with the above calculated and tabulated parameters. Both calculated minimum and maximum values of wood density γ have been used, for both first negative and first positive strokes of the lightning current. The results are shown in Figs. 1 and 2 as a function of the values of the specific energy *W/R* given in Table 1.

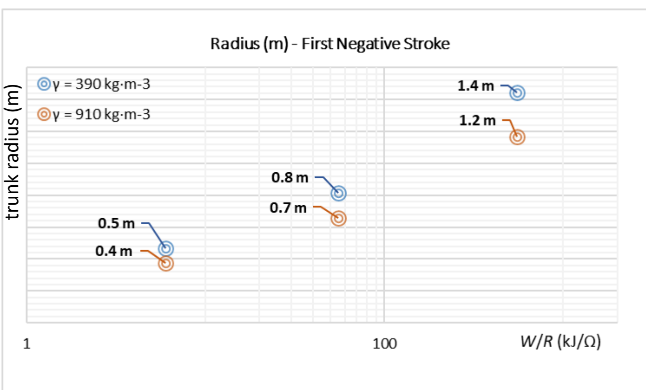

Fig. 1. Critical trunk radius below which the tree may splinetr (first negative stroke).

The calculations show that the worst-case scenario occurs at the occurrence of the first positive impulse stroke with a specific energy *W/R* of 15 MJ/Ω (5% probability of occurrence) and for a wood density γ of 390 kg·m^{-3}. In this scenario, trees with trunk radius less than 3.3 m may not withstand a lightning strike and splinter.

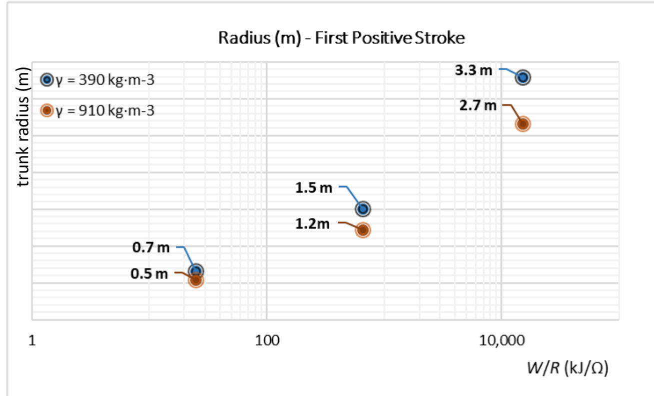

Fig. 2. Critical trunk radius below which the tree may splinter (first positive stroke).

The best-case scenario occurs at the occurrence of the first negative impulse stroke with a specific energy *W*/R of 6 kJ/Ω (95% probability of occurrence) and for a wood density γ of 910 kg·m^{-3} (Fig. 1). In this scenario, trees with trunk radius less than 0.4 m may not withstand a lightning strike and splinter.

III. EQUIVALENT COLLECTION AREA OF A TREE

According to [10] and [11], the vulnerability of a structure to lightning involves the evaluation of its *equivalent collection area* A_D and of the flash density for region in which the structure is located.

A_D is defined as the equivalent area at the ground level, having the equivalent lightning flash vulnerability as the tree. The collection area is determined by the intersection between the earth surface and a straight line with 1/3 slope which passes from the top of the tree of height H and rotates around it (Fig. 3).

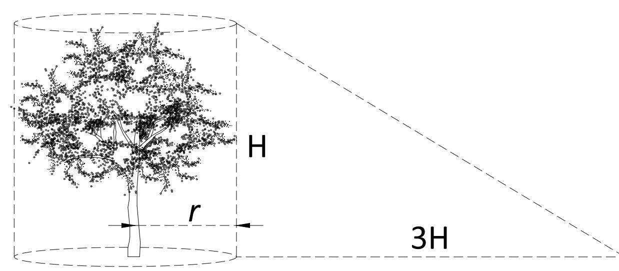

Fig. 3. Equivalent Collection Area of a tree.

Based on the above, A_D (m^2) can be calculated with (6).

$$A_D = \pi(3H+r)^2 \tag{6}$$

where r is the maximum length of the tree canopy.

A_D must be adjusted to include the effects of any objects

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

located within the distance 3H from the tree that can affect the collection area, by multiplying it for the location factor C_D (Table II).

TABLE II
LOCATION FACTOR, C_D

Relative location	**C_D**
Tree surrounded by taller objects within a distance of 3H	0.25
Tree surrounded by objects of equal or lesser height within a distance of 3H	0.5
Isolated tree, with no other objects located within a distance of 3H	1
Isolated tree on a hilltop	2

The location factor accounts for the topography of the site where the tree is growing and may either decrease or increase the collection area. A larger adjusted collection area will correspond to a larger expected annual threat occurrence for the tree, which is, therefore, more likely to be hit by lightning.

Where the equivalent collection area of a tree completely includes another tree's collection area, the covered tree is protected against lightning.

In this study, we have assumed H ranging between 3 m and 30 m, and *r* ranging between 1.5 m and 15 m. To include different shapes of trees in equivalent collection area calculations, we have introduced the form factor κ = H/*r*, equal to 2 and 4 (Fig. 4).

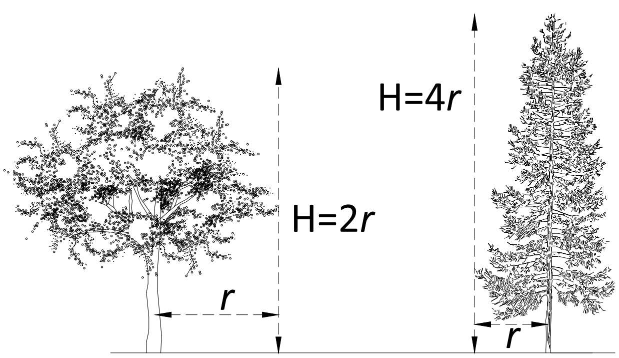

Fig. 4. Form factor H/*r*

The expected annual number of dangerous events N_D (y^{-1}) due to lightning flashes striking a tree can be calculated with (7) [8][9].

$$N_D = N_G \cdot A_D \cdot C_D \cdot 10^{-6} \quad (7)$$

where N_G is the annual lightning ground flash density [$km^{-2} \cdot y^{-1}$]; A_D is the collection area of the tree (m^2); C_D is the location factor of the tree.

N_G depends on the thunderstorm activity of the region where the tree is located, and its values may be reported in lightning flash density maps. For instance, in 2019, in the state of Florida (U.S.), a total lightning density of cloud-to-ground strokes per square kilometer of 87.93 was observed [12], whereas [11] reports a maximum of 0.5 to 1 flash per square kilometer per year in the state of California.

Unusual weather events, however, such as the *dry thunderstorms,* occurred in Northern California, the month of August 2020, produced over 12,000 lightning strikes in four days over the Bay Area, which spiked 585 wildfires [13]. The above events caused a lightning ground flash density well above the values indicated in applicable standards.

IV. RISK ASSESSMENT OF DIRECT FLASHES TO TREES

The risk assessment of direct flashes to trees compares the annual threat occurrence R_x for the tree, which is based on N_D, to the tolerable risk R_T (y^{-1}).

Typical values of tolerable risk are given in Table III [10].

TABLE III
TOLERABLE RISK, R_T

Types of loss	**R_T (y^{-1})**
Loss of human life or permanent injuries	10^{-5}
Loss of cultural heritage	10^{-4}
Loss of economic value	10^{-3}

The annual risk R may be expressed by equation (8).

$$R_x = N_D \times P_x \times L_x \quad (8)$$

P_x is the probability of damage (to a tree or persons), and L_x is the consequent loss (human life or physical damage to a tree). Protection measures will be required if $R_x > R_T$.

Trees may be considered monumental for historical reasons, aesthetic value, but also for their role in preserving rare and endangered species [14]. Lightning strikes trees may endanger monumental trees, and the risk of loss of cultural heritage R_B must be evaluated.

Lightning striking trees may also endanger the public, if trees are located in areas with continuous presence of persons (e.g., national parks). The lightning strike may in fact cause dangerous touch and step voltages [15]. Thus, the risk R_A of loss of human life and injury to living beings by electric shock must also be considered.

A. *Risk of loss of human life and permanent injury to living beings.*

The risk R_A of loss of human life and permanent injury to living beings may be determined with equation (9).

$$R_A = N_D \times P_A \times L_T \times r_t = N_D \times 10^{-4} \quad (9)$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

P_A is the probability that the lightning flash will cause shock to living beings around the tree. If the tree is not protected and grows in a crowded area, P_A=1.

L_T is the relative numbers of victims injured by electric shock, which is assumed to be 10^{-2} [10]. r_t is a factor reducing the loss of human life thanks to the agricultural soil around the tree (i.e., low resistivity), which is also 10^{-2} [10].

B. Risk of loss of cultural heritage

The risk R_B of loss of cultural heritage (e.g., monumental trees) may be determined with equation (10).

$$R_B = N_D \times P_B \times \frac{c}{c_t} \times r_f = N_D \times 10^{-1} \quad (10)$$

P_B is the probability of a physical damage occurring to the tree due to a lightning flash. If the tree is not protected by a lightning protection system (LPS), P_B =1.

c is the mean value of the possible loss, and c_t is the value of the tree. In the case of lightning strike, the tree may be completely destroyed, therefore the ratio c/c_t equals 1.

r_f is a factor reducing the loss due to physical damage depending on the risk of fire, which for a tree is high; therefore, r_f = 0.1.

V. Lightning Protection Assessment

The value of the critical height H that require a tree to have protection against lightning strikes can be studied as a function of κ, N_G and C_D. The critical height H has been studied in relation to both the risk of loss of human life and cultural heritage.

Substituting (6) into (9) and solving for H, we obtain Eq. 11, which identifies the critical height $H^{(RA)}$ for which the risk of loss of human life R_A is greater than the tolerable value of 10^{-5} y^{-1} (Table 3).

$$H^{(R_A)}(\kappa, N_G, C_D) = 178\frac{\kappa}{3\kappa+1}\sqrt{\frac{1}{N_G C_D}} \quad (11)$$

Equation (11) is graphed in Fig. 5 and Fig. 6, for κ = 2 and κ = 4, respectively.

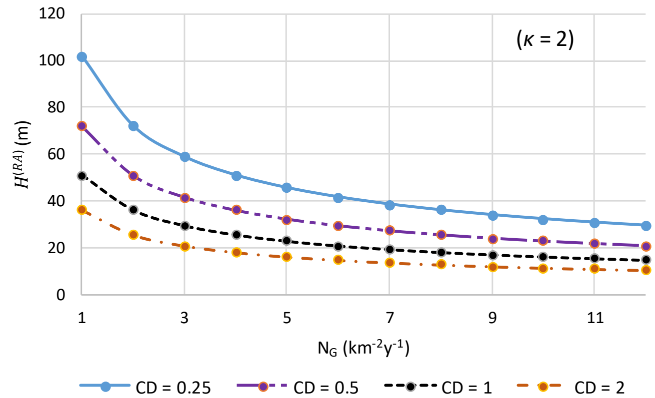

Fig. 5. Critical heights $H^{(RA)}$, for κ = 2.

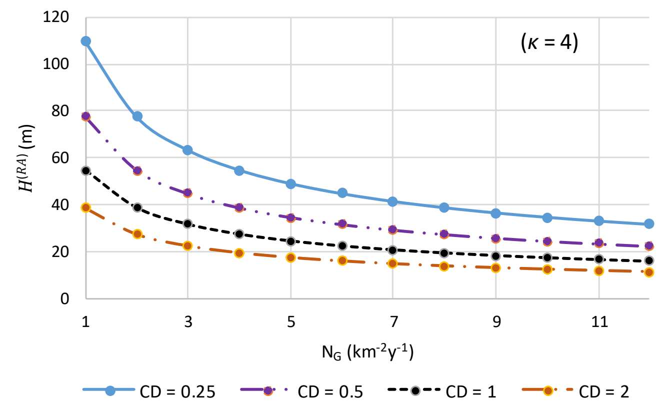

Fig. 6. Critical heights $H^{(RA)}$, for κ = 4.

It can be clearly seen that increasing values of N_G, decrease the critical height of trees which requires protection against the hazard of touch and step voltages due to lightning. Increasing values of C_D cause the same effect.

In the case of unusual weather events (i.e., $N_G \geq 90$ km^{-2}y^{-1}), the height of the trees requiring protection to lower the risk of loss of human life is below around m. In the case of standard weather events (i.e., N_G = 1 km^{-2}y^{-1}) [11], the critical height is above 100 m.

Equation 12 identifies the height $H^{(RB)}$ for which the risk of loss of cultural heritage R_B is greater than the tolerable value of 10^{-5} y^{-1}.

$$H^{(R_B)}(\kappa, N_G, C_D) = 17.8\frac{\kappa}{3\kappa+1}\sqrt{\frac{1}{N_G C_D}} \quad (12)$$

Equation 12 is graphed in Fig. 7 and Fig. 8, for κ = 2 and κ = 4, respectively.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

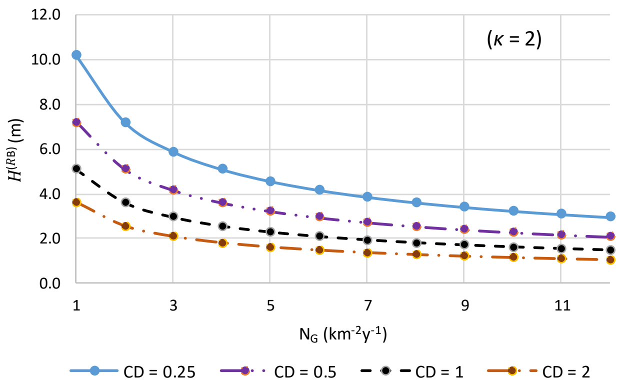

Fig. 7. Critical heights $H^{(RB)}$, for $\kappa = 2$.

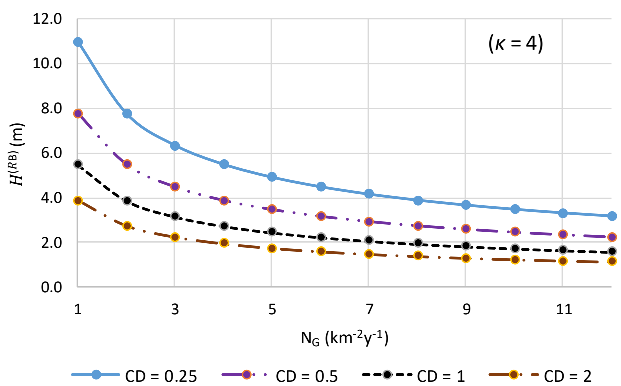

Fig. 8. Critical heights $H^{(RB)}$, for $\kappa = 4$.

The trend of the critical height $H^{(RB)}$ for increasing values of N_G and C_D is similar to that of $H^{(RA)}$.

The worst-case scenario for the critical heights $H^{(RA)}$ and $H^{(RB)}$ is for an isolated tree on a hilltop (i.e., C_D = 2) and under unusual lightning events (i.e., N_G = 90 $km^{-2}y^{-1}$), which is shown in Fig. 9, for $\kappa = 2$ and $\kappa = 4$.

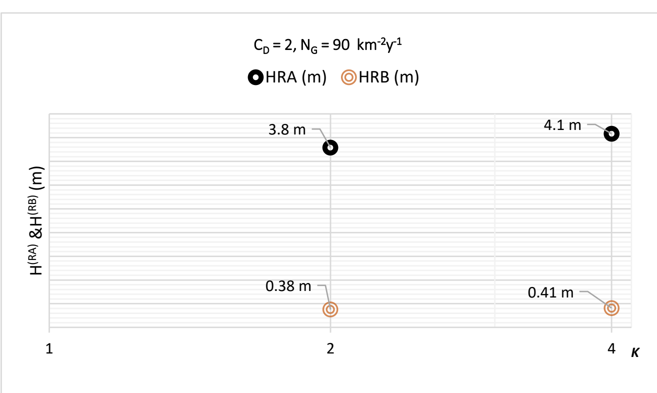

Fig. 9. Worst-case scenario for $\kappa = 2$ and $\kappa = 4$ (C_D =2, N_G = 90 $km^{-2}y^{-1}$)

The best-case scenario for the critical heights $H^{(RA)}$ and $H^{(RB)}$ is for a tree surrounded by taller objects within a distance of 3H (i.e., C_D = 0.25) and under standard lightning events (i.e., N_G = 1 $km^{-2}y^{-1}$) [11], which is shown in Fig. 10, for $\kappa = 2$ and $\kappa = 4$.

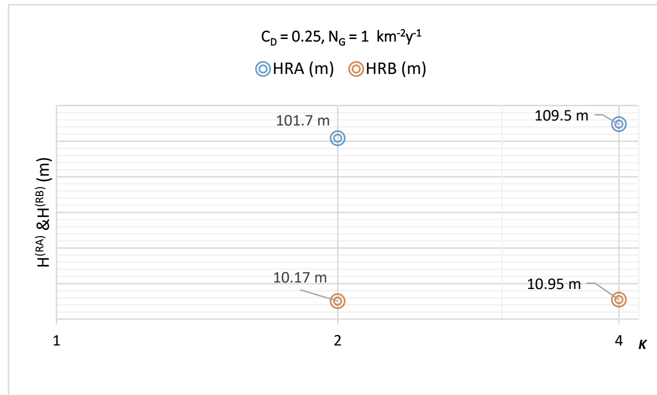

Fig. 10. Best-case scenario for $\kappa = 2$ and $\kappa = 4$ (C_D =0.25, N_G = 1 $km^{-2}y^{-1}$).

VI. Tree Lightning Protection System

The tree lightning protection systems (TLPS) provides a preferred point for the lightning attachment and a pathway to ground to the lightning current. This pathway reduces the risk of fire for the struck tree, as well as for neighboring trees, possibly due by side flash.

The components of a TLPS embedded in a tree are shown in Fig. 11.

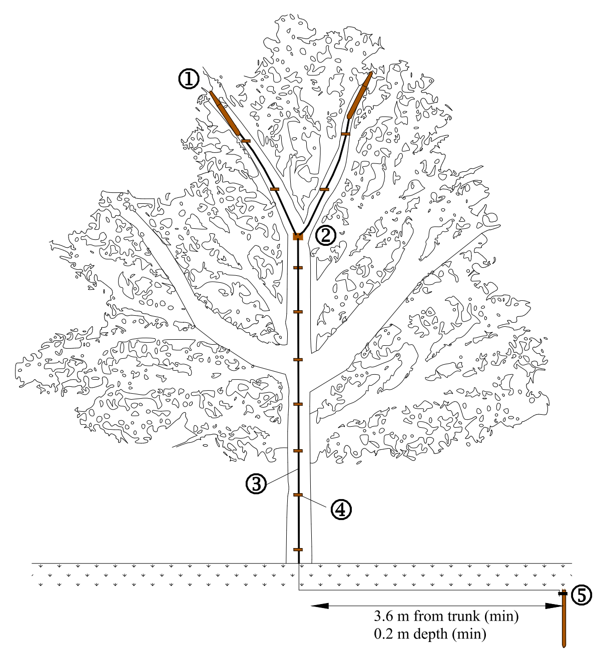

Fig. 11. Tree Lightning Protection System components. ① air terminal (typ.); ② side-by-side connector; ③ down-conductor; ④ tree drives (typ.); ⑤ ground rod and clamp.

Aluminum wires or accessories should not be used on trees due to issue related to the overall strength and the corrosion resistance; only materials made of copper and bronze alloys should be used [16]. The down-conductors are attached to the tree by means of fasteners, hammer driven through the bark and into the tree; fasteners must be placed at not more than 2 m apart. Conductors are flexible to allow for the swaying of the trunk and branches, and components are adjustable to allow for the growth of the tree.

The ground electrode should be located at least 3.6 m from the trunk to avoid damages to the root [16]. The air terminal tip may be sharp or blunt.

An economic alternative to a TLPS for each single tree may be an overhead ground wire (OHGW), typical of transmission lines.

The presence of the OHGW prevents the flow of the lightning current through the down-conductor (Fig. 11), which further reduces the risk of fire.

The OHGW may be mechanically supported by the tallest trees (Fig. 12a), and locally grounded. If the tree is not deemed able to withstand the mechanical load imposed by the OHGW, grounded metal poles may be used (Fig. 12b).

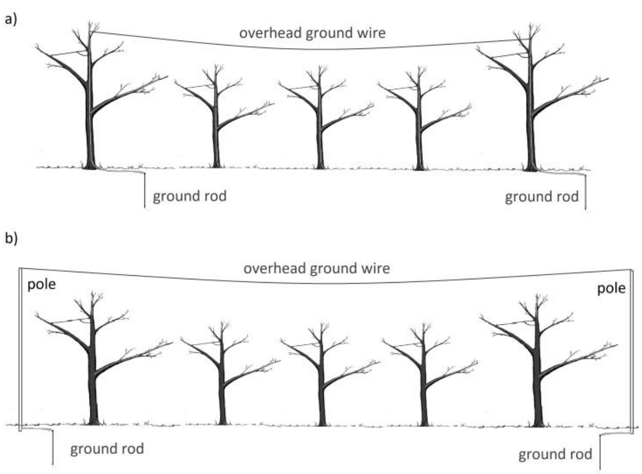

Fig. 12. a) OHGW supported by the tallest trees; b) OHGW supported by grounded metal poles.

The solution with metal poles may add additional costs to this protective configuration, which does not use the tree as a mechanical support; however, the cost is still offset by the economy of scale created by the simultaneous protection of multiple trees.

In Table IV, an economical study of the proposed solution with steel OHGW and with single TLPS is reported for two cases (trees with radius 1.5 m and trees with radius 5 m); the comparison shows when the OHGW can be more economically convenient than the TLPS. The cost of the single TLPS is estimated between US$ 200 and US$ 400 [17]-[18]. The cost of a wooden pole longer than 15 m is estimated between US$ 1,000 and US$ 1,500, whereas the cost for the OHGW is estimated about 3.5 US$/m.

The calculations show that for the two cases in question, poles and OHGWs are more convenient when the number of trees to be protected ranges between 8 and 10.

It is worth noting that in many cases poles and steel OHGWs have almost no visual impact on the environment and on the landscape. OHGWs are thin conductors and poles can be made of wood, which allows them to blend in the forested area being protected. Poles do not require large cross-sections, since the mechanical stress to which they may be subjected is minimal (essentially wind load and the lateral OHGW pull). The installation of foundation blocks does not require large and deep excavations, therefore it does not jeopardize tree’s roots.

The OHGWs is normally out of sight, given the height of the installation.

TABLE IV
COST COMPARISON

Number of trees with radius 1.5 m to be protected										
Costs [US$]	3	4	5	6	7	8	9	10	15	20	30
single TLPS	1,200	1,600	2,000	2,400	2,800	3,200	3,600	4,000	6,000	8,000	12,000
LPS with OHGW	3,053	3,070	3,088	3,105	3,123	3,140	3,158	3,175	3,263	3,350	3,525
Number of trees with radius 5 m to be protected											
Costs [US$]	3	4	5	6	7	8	9	10	15	20	30
single TLPS	600	800	1,000	1,200	1,400	1,600	1,800	2,000	3,000	4,000	6,000
LPS with OHGW	2,021	2,028	2,035	2,042	2,049	2,056	2,063	2,070	2,105	2,140	2,210

VII. CONCLUSION

This paper is based on [20]. Lightning strike induced fires have become a concerning world issue. As a byproduct of the climate change, lighting strikes have been the catalyst of massive wildfires, threating persons, and assets.

In this paper, the authors have discussed the lightning strike withstand capability of trees, by analytically identifying the minimum trunk radius that allows the tree to sustain the first positive and negative strikes without suffering a splintered bark and exploded wood, which may ignite the surrounding vegetation.

In the best-case scenario, which features a 95% probability of lightning strike occurrence, trees with a trunk radius of 0.4 m or less may not withstand a 6 kJ/Ω first negative impulse stroke and splinter.

The critical heights $H^{(RA)}$ and $H^{(RB)}$ which require trees to be protected against lightning strikes to prevent loss of human life and cultural heritage, respectively, have been analyzed as a function of the tree shape factor κ, the ground flash density N_G and the location factor C_D.

A tree surrounded by taller objects within a distance of 3H (i.e., $C_D = 0.25$) and under standard lightning events (i.e., $N_G = 1$ km^{-2}y^{-1}) (i.e., best-case scenario), will require a TLPS for protection against loss of human life only if its height is 101.7 m or higher; or for protection against loss of cultural heritage, only if its height is 10.17 m or higher.

Preliminary tree lightning protection solutions have been proposed, which include TLPS embedded in trees, and overhead ground wires to protect group of trees. In further studies, economic aspects of the deployment TLPSs in forested areas will be presented.

References

[1] J.A. Lutz et Al.: "Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA." International Journal of Wildland Fire 2009, 18, 765-774.

[2] IEC 62305-1: "Protection against lightning – Part 1: General principles". 2010-12.

[3] Complete Probabilistic Method, available at: https://franklin-france.com/en/guide/complete-probabilistic-method/

[4] M. Di Stefano, C. Mazzetti, "Probabilistic Approach for Lightning Protection of Structures: Application Criteria for Protective System Design", IEEE Transactions on Industry Application, Volume IA-19, No. 6, November/December 1983, pages 920-931.

[5] R. Tommasini, F. Palamara, E. Pons: "The lightning protection of trees effects of lightning strikes and risk management." 29th International Conference on Lightning Protection, 2008, Uppsala, Sweden.

[6] M. Mitolo, M. Tartaglia: "An Analytical Evaluation of the prospective I^2t to Assess Short Circuit Capabilities of Cables and Busways". IEEE Transactions on Power Delivery, Volume 25, No. 3, July 2010, pages 1334-1339.

[7] Babrauskas, Vytenis. (2002). "Ignition of Wood: A Review of the State of the Art." Journal of Fire Protection Engineering - J FIRE PROT ENG. 12. 163-189. 10.1177/10423910260620482.

[8] C. Skaar: "Electrical Properties of Wood. In: Wood-Water Relations. Springer Series in Wood Science." Springer, Berlin, Heidelberg, 1988.

[9] Department of Agriculture, Forest Service, Forest Products Laboratory: "Wood Handbook-Wood as an engineering material. General Technical Report FPL-GTR-190." Madison, WI, 2010.

[10] IEC 62305-2: "Protection against lightning - Part 2: Risk management." 2010.

[11] NFPA 780: "Standard for the Installation of Lightning Protection Systems." 2020 edition.

[12] Vaisala Annual Lightning Report 2019. https://www.vaisala.com/en/system/files/documents/Vaisala-Annual-Lightning-Report-2019_0.pdf. Retrieved November 11, 2020.

[13] Nicco, Mike, Tuma, Drew, Argen, Lisa (August 17, 2020). "More lightning, thunderstorms hit Bay Area as heat wave continues." ABC7 San Francisco. Retrieved September 1, 2020.

[14] Zapponi L, Mazza G, Farina A, Fedrigoli L, Mazzocchi F, Roversi PF, Sabbatini Peverieri G, Mason F: "The role of monumental trees for the preservation of saproxylic biodiversity: re-thinking their management in cultural landscapes." Nature Conservation 19. (July 2017).

[15] M. Mitolo and H. Liu, "Touch Voltage Analysis in Low-Voltage Power Systems Studies," in IEEE Transactions on Industry Applications, vol. 52, no. 1, pp. 556-559, Jan.-Feb. 2016.ANSI A300 (Part 4): "Lightning Protection System." 2008.

[16] ANSI A300 (Part 4): "Lightning Protection System." 2008.

[17] American Arborist Supply, Lightning Protection, available at: https://www.arborist.com/category/7/Lightning-Protection.html

[18] Tree Lightning Protection, available at: https://www.fixr.com/costs/lightning-rod#:~:text=Tree%20Lightning%20Protection,-If%20you%20have&text=Without%20these%20systems%2C%20trees%20can,the%20amount%20of%20work%20required.

[19] The financial case – Why is the pole so cost effective? Available at: https://polesaver.com/blog/the-financial-case-why-is-it-so-cost-effective/

[20] M. Mitolo, E. Pons, G. Zizzo "Protection of Trees Against Lightning Strikes as a Measure to Prevent Fires and Loss of Human Life." Proceedings of the 2021 IEEE/IAS 57th Industrial and Commercial Power Systems Technical Conference (I&CPS), 27 April 2021.

Massimo Mitolo (Fellow, IEEE) has been awarded the Knighthood in the Order of Merit of the Italian Republic for merit acquired by the nation in recognition of his scientific work. Dr. Mitolo received the Ph.D. in Electrical Engineering from the University of Napoli "Federico II", Italy. He is a Fellow of IEEE "for contributions to the electrical safety of low- voltage systems", and a Fellow of the Institution of Engineering and Technology (IET) of London (UK). He is a registered Professional Engineer in the state of California and in Italy. Dr. Mitolo is currently a Full Professor of Electrical Engineering at Irvine Valley College, Irvine, CA, USA, and a Senior Consultant in the matter of failure analysis and electrical safety with Engineering Systems Inc., ESi. Professor Mitolo's research and industrial experience are in analysis and grounding of power systems, and electrical safety engineering. Dr. Mitolo has authored over 160 journal papers and the books "Electrical Safety of Low-Voltage Systems" (McGraw-Hill), "Laboratory Manual for Introduction to Electronics: A Basic Approach" (Pearson), "Analysis of Grounding and Bonding Systems" (CRC Press), "Electrical Safety Engineering of Renewable Energy Systems" (John Wiley & Sons). He is currently the deputy Editor-in-Chief of the IEEE Transactions on Industry Applications. He is active within the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society (IAS) in numerous committees and working groups. The recipient of the IEEE Region 6 2015 Outstanding Engineer Award, Dr. Mitolo has earned nine Best Paper Awards, numerous recognitions, among which are the IEEE Ralph H. Lee I&CPS Department Prize Award, the IEEE I&CPS 2015 Department Achievement Award, and the James E. Ballinger Engineer of the Year 2013 Award from the Orange County Engineering Council.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2021.3084122, IEEE Transactions on Industry Applications

Enrico Pons (M'15) received the master degree in electrical engineering in 2004 and the Ph.D. in industrial safety and risk analysis in 2008 from Politecnico di Torino, Torino, Italy. He is currently associate professor at Politecnico di Torino, where he teaches electrical installations. His research activities include complexity in energy systems, power systems security, complex networks methodologies for the analysis of power systems vulnerability, real-time simulation of power systems, integration of renewable generation in distribution networks, smart metering, traction electrification systems and electrical safety. He co-authored more than 80 publications, published in international
conferences proceedings and in international journals.

Gaetano Zizzo (SM'17) is Associate Professor of Electrical Power Systems at the University of Palermo, Italy, where he obtained his M.S. degree in 2002 and his Ph.D. degree in Electrical Engineering in 2006. Since 2006 he works at the Engineering Department of the same university. In 2017 he was elected Senior Member IEEE as a member of the Industry Application Society. He is involved in the activities of the IEEE Standard Association. His current research interests include electrical safety, power systems design, management, and optimization, smart grids and stability analysis.