Lightning Risk Assessment of Rooftop Photovoltaic Systems: A Case Study Approach

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***Abstract*—The growth of photovoltaic (PV) technology in a global context is evident due to a drop in costs. In Africa, there is potential for expansive growth of solar PV due to favourable climatological conditions. PV systems, due to their inherent exposure to the elements, are prone to damage caused by lightning. For small- to medium-scale rooftop PV systems in particular, there is currently no well-defined methodology for assessing risk of lightning damage and determining protection requirements. In this paper, a framework for risk assessment of rooftop PV systems is proposed. The framework is applied to two practical case studies. It is found that the larger a rooftop PV system is, the higher the contribution of the PV system to the overall risk of lightning damage to the structure. These findings will lead to the further development of PV standards where in both the African and global context, continuous knowledge production in this regard is necessary.**

***Index Terms*—Lightning protection, Photovoltaic systems, Risk assessment framework**

I. Introduction

Worldwide growth of photovoltaic (PV) systems is evidence of the need for renewable energy. From 2015 to 2016, there has been a global increase in grid-tied installations of more than 50% from 50 GW to 76 GW [1]. This is largely due to a drop in component costs. In Africa, the primary source of energy generation comes from fossil fuels [2] with, in 2016, a total of only 0.1% of energy generation from solar PV [3]. Despite this, there is significant potential for growth of solar PV in Africa due to the abundance of favourable solar irradiation conditions throughout the continent [4]. This potential exists for PV installations ranging from small- to utility-scale. Due to a lack of infrastructure in rural areas, small-scale PV systems with storage are an attractive potential investment. Likewise in urban and suburban areas, home owners, businesses and institutions also install PV systems for decreased reliance on grid-supply, backup power and future cost savings.

Typically, small- to medium-scale PV systems used in such applications are installed on rooftops. Rooftop PV systems are prone to damage from the elements. One such source of damage is lightning. Lightning flashes are a common global occurrence. Some areas in Africa, particularly in Central Africa, experience high lightning ground flash densities [5]. These high ground flash densities, coupled with the growth of rooftop PV systems, are suggestive of the increased risk of lightning damage. Lightning protection standards for rooftop PV are underdeveloped with no well-defined methodology for analysing risk and determining protection requirements. In this paper, a novel framework for risk assessment of lightning damage to rooftop PV systems is proposed. The framework is applied to two practical case studies to comparatively analyse the risk of damage to rooftop PV systems of different sizes.

II. Background

The risk assessment process for analysing the risk of lightning damage to a structure is detailed in the IEC 62305-2 standard [6]. In order to determine the need for a lightning protection system (LPS), the numerical risk of lightning damage to a structure is calculated. If the risk of lightning damage to the structure, R, is greater than the threshold risk, R_T, lightning protection for the structure is required. The risk components are calculated using (1):

$$R_X = N_X \times P_X \times L_X \tag{1}$$

where R_X is the risk component, N_X is the annual number of dangerous events, P_X is the probability of damage and L_X is the resultant loss. Depending on the type of structure, associated loss and type of damage, there are four types of risks that could be determined with each having a specified threshold value. These risks, as detailed in IEC 62305-2, are summarised in Table I.

TABLE I: Risk Factors and their Associated Risk Threshold Values

Risk	Threshold Risk
R_1 - Risk of loss of human life	10^{-5}
R_2 - Risk of loss of service to the public	10^{-3}
R_3 - Risk of loss of cultural heritage	10^{-4}
R_4 - Risk of economic loss	10^{-3}

For rooftop PV systems, the more pertinent losses under consideration would be the loss of human life and economic loss. This is due to the scale of the system. The risk constituents used to calculate the total risk for the associated losses are based on the lightning strike point with respect to the structure. The risk components considered, with respect to the lightning strike points, as detailed in IEC 62305-2, are summarised in Table II.

TABLE II: Lightning Strike Points and Associated Risk Constituents

Strike Point	Risk Constituents
S_1 - Direct to structure	R_A, R_B, R_C
S_2 - Near structure	R_M
S_3 - Direct to line	R_U, R_V, R_W
S_4 - Near line	R_Z

When considering a rooftop PV system, the lightning strike points could be amended due to the location of the PV array. A direct strike to the PV array may be significantly consequential in the value of the risk. The overall risk assessment methodology as summarised in this section has not been adapted specifically for rooftop PV systems. Hence, integration of the rooftop PV system into the evaluation of risk is an essential aspect to address.

In terms of existing research on evaluation of lightning risk for PV systems, not much work has been done for rooftop PV systems. In [7]–[11], research has been done on risk assessment for PV systems. Most of this research takes into consideration the risk for free-field, utility-scale installations. However, in [8], the risk of lightning damage to a rooftop PV system is assessed. The methodology used herein is to consider the rooftop PV system as the sole point of damage - i.e. the structure in which the PV system is installed is not considered as part of the risk assessment. Although in the aforementioned paper it is shown that there is a risk of lightning damage to a rooftop PV system, the structure itself is not assessed. Therefore, in this paper, the approach used to calculate risk of damage to a rooftop PV system is to consider a rooftop PV system and the associated structure holistically in order to develop a framework for lightning protection for a PV-building structure as a whole.

III. Methodology

A. Development of Framework

The development of a framework for lightning risk assessment of rooftop PV systems requires a novel approach. As previously mentioned, the PV system and structure will be viewed holistically. When installing a rooftop PV system, the physical building structure is retrofitted due to the mounting of the modules of the PV array. Additionally, the direct connection of the incoming PV system is essentially a retrofitting of the electrical reticulation of the building. Taking this into consideration, the rooftop PV system is integrated into the risk of damage to a structure by:

- Including an additional strike point direct to the rooftop PV array, and;
- considering the PV system as an additional incoming 'line'.

This takes into account the aspects of retrofitting of a structure with a rooftop PV system. The additional strike point is considered as a direct strike to the PV array in addition to those indicated in Table II. Also, the PV system as an incoming 'line' is included together with the typical incoming telecommunication and power lines. This information is better understood as an illustration as shown in Fig. 1.

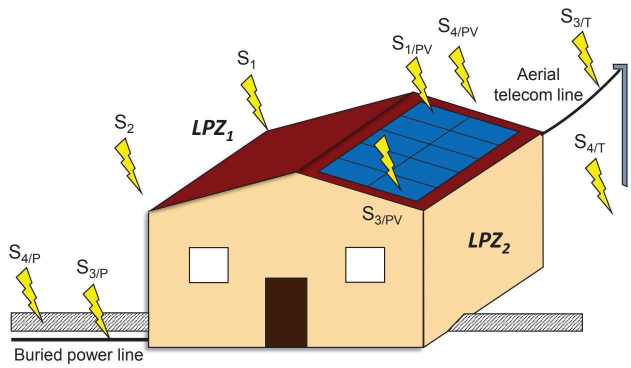

Fig. 1: Strike points and protection zones for a structure fitted with a rooftop PV system

Fig. 1 indicates that all considerations are taken with regards to the installation of the rooftop PV system. Pertinently, lightning protection zones (LPZs) are designated for the structure. Due to the PV array being the only component of the system residing externally, only the economic loss is considered in LPZ_1 for a direct strike condition. However, for an indirect strike, all the risk constituents are considered in terms of electromagnetic effects in LPZ_2. Table III summarises the strike points and risk constituents used for the calculation of the total risk of damage. Damages D1, D2 and D3 for injury to living beings by electric shock, physical damage and failure of electrical and electronic systems respectively, are detailed in IEC 62305-2.

TABLE III: Risk constituents and type of damage associated with lightning strike points

Strike point	Risk constituent	Damage
S_1	R_A, R_B, R_C	D1, D2, D3
$S_{1/PV}$	$R_{A/PV}$, $R_{B/PV}$, $R_{C/PV}$	D1, D2, D3
S_2	R_M	D3
$S_{3/T}$	$R_{U/T}$, $R_{V/T}$, $R_{W/T}$	D1, D2, D3
$S_{3/P}$	$R_{U/P}$, $R_{V/P}$, $R_{W/P}$	D1, D2, D3
$S_{3/PV}$	$R_{U/PV}$, $R_{V/PV}$, $R_{W/PV}$	D1, D2, D3
$S_{4/T}$	$R_{Z/T}$	D3
$S_{4/P}$	$R_{Z/P}$	D3
$S_{4/PV}$	$R_{Z/PV}$	D3

These strike points fully consider the rooftop PV system in the calculation of lightning risk and would hence be representative of the worst case scenario risk conditions. Each of the risk components applicable to the PV system are added to the respective risk equations for calculating R_1 to R_4. This framework for calculating lightning risk will be applied to two practical case studies.

B. Scenario Analysis

To understand the impact that a rooftop PV system has on the risk of lightning damage to a structure, two basic scenarios are analysed:

1) The risk of lightning damage to the structure as is.
2) The risk of lightning damage to the structure when fitted with a rooftop PV system.

Under these circumstances, the impact of the PV system on the risk to the structure can be quantified. For comparison purposes, two practical case studies are investigated. One is a typical residential structure fitted with a small-scale rooftop PV system and the other a commercial structure fitted with a medium-scale rooftop PV system. Both structures are located in Johannesburg, South Africa which is an important consideration for the value of the annual lightning ground flash density.

IV. Case Studies

A. Residential Structure

The residential structure investigated is a suburban residence in the north of Johannesburg. To conduct a lightning risk assessment and hence determine the need for protection, the properties of the structure and the PV system must be determined. The residence is fitted with a 2.5 kWp hybrid PV system consisting of battery-form storage. Fig. 2 is a Google Earth image illustrating the rooftop under consideration.

Fig. 2: Google Earth image of the residence in Johannesburg indicating the rooftop structural layout

Additionally, Fig. 3 is a photograph of the rooftop PV array located on the north facing roof of the structure.

Fig. 3: Photograph indicating the location of the PV array on the rooftop of the residential structure

To calculate the collection area of the structure and the PV array, the dimensions of each are required. This will be used to calculate the number of dangerous events. The house has a one storey height with the highest point being the top of the tank of the rooftop solar geyser. This is taken into account for the calculation of the collection area of the structure. The top view of the dimensions are illustrated in Fig. 4.

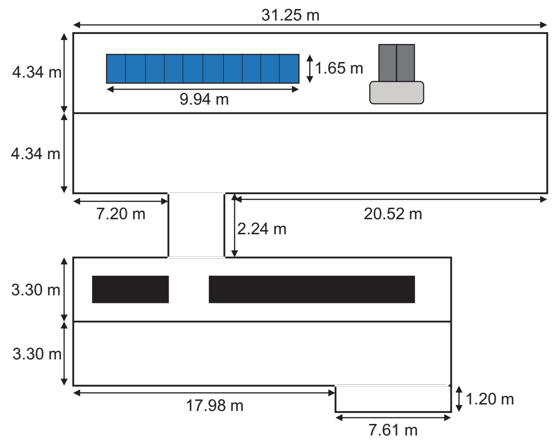

Fig. 4: Top view of the dimensions of the residential structure and the rooftop PV system

The height of the structure, taking into account an approximate 22° roof tilt and the height of the solar geyser tank, is about 5 m. The structure is considered as a single block to simplify calculation of collection area and hence makes consideration of worst case scenario conditions. The collection area of the structure is calculated using (2) as detailed in IEC 62305-2 [6]:

$$A_D = (L \times W) + [2 \times (3 \times H)(L + W)] + [\pi \times (3 \times H)^2] \quad (2)$$

where L is the length of the structure (m), W is the width (m) and H is the height (m). Using dimensions of $L = 18.72m$, $W = 31.25m$ and $H = 5m$, the collection area is calculated as $A_D = 2791m^2$. Similarly, for the collection area of the PV array, (3) is used as adapted from (2):

$$A_{D/PV} = (L_{PV} \times W_{PV}) + [2 \times (3 \times H)(L_{PV} + W_{PV})] + [\pi \times (3 \times H)^2] \quad (3)$$

where L_{PV} is the length of the PV array (m) and W_{PV} is the width (m). Using dimensions of $L_{PV} = 1.65m$, $W_{PV} = 9.94m$ and $H = 5m$, the collection area is calculated as $A_{D/PV} = 1071m^2$.

In addition to collection area, the annual lightning ground flash density is required to calculate the number of dangerous events. The South African Weather Service (SAWS) provides data for the recorded ground flash densities across the country as determined using the South African Lightning Detection Network (SALDN). The latest publicly available data is found in the South African standard SANS 10313 [12] compiled in 2012. For the structure located in Johannesburg, the given annual ground flash density of 11.7 flashes/km^2 is used in the calculation of the number of dangerous events.

For the calculation of risk, it is assumed that the electrical reticulation of the structure conforms to the South African standard, SANS 10142-1 [13] for low voltage (LV) wiring. There is a buried incoming power line and aerial incoming telecommunication line. Also, the LPZs under consideration are as illustrated in Fig. 1 with one outside zone, LPZ_1, and one interior zone, LPZ_2. The main specifications of the structure fitted with the rooftop PV system, in terms of the parameters required to calculate the risk constituents, are indicated in Table IV.

TABLE IV: Specifications of the Residential Structure

Environment and structure		
Input parameter	*Symbol*	*Value*
Ground flash density (1/km^2/year)	N_G	11.7
Structure collection area (m^2)	A_D	2791
PV array collection area (m^2)	$A_{D/PV}$	1071
LPS installed (none)	P_B	1
Equipotential bonding (LPS - none)	P_{EB}	1
Power line		
Installation factor (buried)	C_I	0.5
Line type factor (LV)	C_T	1
Telecom line		
Installation factor (aerial)	C_I	1
Line type factor (telecom)	C_T	1
PV 'line'		
Installation factor	C_I	1
Line type factor (LV)	C_T	1
Zone 1 (consists of rooftop PV array)		
Type of floor (ceramic)	r_t	10^{-3}
Risk of fire (ordinary)	r_f	10^{-2}
Coordinated line SPDs (none)	P_{SPD}	1
Persons in zone (none)	-	0
Zone 2 (inside structure)		
Type of floor (ceramic)	r_t	10^{-3}
Risk of fire (ordinary)	r_f	10^{-2}
Coordinated line SPDs (none)	P_{SPD}	1
Persons in zone (4)	-	1

The risks under consideration are the loss of human life and economic loss. These are the pertinent considerations for typical small-scale rooftop PV systems. Using the parameters in Table IV (including those not indicated) and equations found in [6], the results of the risk assessment for the aforementioned scenarios are indicated in Table V. The results are also illustrated graphically in Fig. 5.

The results indicate that the risk of loss of human life is almost four times above the threshold of 10^{-5}. This is probably due to the fairly high lightning ground flash density value. The risk of economic loss is below the threshold of 10^{-3}. Nevertheless, an LPS is required and hence will reduce the risk in both cases. The interior zone is shown to be the pertinent area of risk which is associated with the incoming lines. The rooftop PV system has minimal influence on the risk of loss of human life. There is an increase in risk of only 1.77%. Likewise, for the risk of economic loss with an increase of only 3.47%. The structure and PV system are however viewed holistically, hence an appropriate LPS is required.

TABLE V: Results of the lightning risk assessment for the residential case study

		Structure	*Structure with PV*
Human life (R_1) $\times 10^{-5}$	LPZ_1	-	-
	LPZ_2	3.894	3.963
	Total	**3.894**	**3.963**
Economic (R_4) $\times 10^{-3}$	LPZ_1	-	0.000689
	LPZ_2	0.0404	0.0411
	Total	**0.0404**	**0.0418**

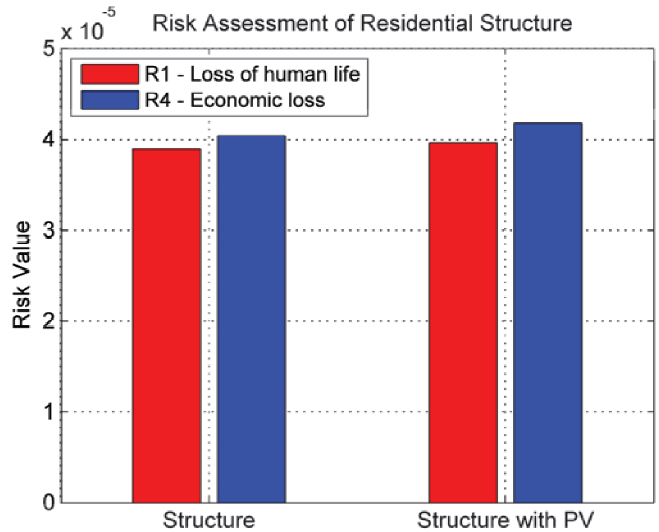

Fig. 5: Bar chart illustrating the results of the risk assessment for the residential structure fitted with a rooftop PV system

B. Commercial Structure

The commercial structure investigated is the Genmin Laboratories at the University of the Witwatersrand in Johannesburg. The structure is due to be installed with a grid-tied, 135 kWp rooftop PV system with a high percentage of rooftop coverage. The properties of the structure are determined in order to conduct a lightning risk assessment and hence determine the need for an LPS. Fig. 6 is a Google Earth image illustrating the rooftop of the laboratory structure.

As with the residential structure, the dimensions of the commercial structure are required to calculate the collection area of the structure and the PV array. Fig. 7 illustrates the dimensions of the structure and the layout of the modules on the roof of the structure.

The structure is located on an inclined plane where from ground level, one side is at two storeys high with the other side at three storeys. These storeys are not standard in height therefore adjustments to typical values are made. To investigate the risk of lightning damage under worst possible conditions,

Fig. 6: Google Earth image of the Genmin Laboratories in Johannesburg indicating the rooftop structural layout

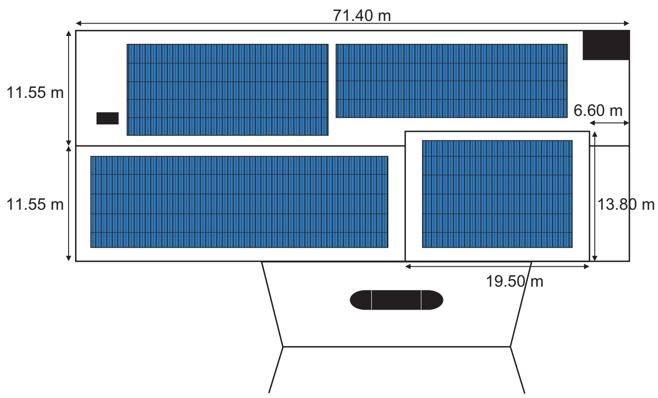

Fig. 7: Top view of the dimensions of the commercial structure and the rooftop PV system

the structure is considered as a three storey building. Additionally, there is a protruding section on the north east side of the roof as shown in Fig. 8.

The heights of the structure with and without the protruding rooftop section (not taking into account the slight roof incline) are estimated to be 20 m and 15 m respectively. To calculate the collection area of the structure, the protruding section is taken into consideration. According to IEC 62305-2 [6], the collection area of the structure is the greater between a calculation using (2) and (4):

$$A_D{'} = \pi \times (3 \times H_P)^2 \tag{4}$$

where $A_D{'}$ is the collection area of the structure under consideration of the protruding section (m^2) and H_P is the total height of the structure with the protruding section (m). Therefore, using (2), with $L = 23.1m$, $W = 71.4m$ and $H = 15m$, the collection area $A_D = 16516m^2$. Using (4), with $H_P = 20m$, the collection area $A_D{'} = 11310m^2$. Hence, the collection area for the structure is selected as $A_D = 16516m^2$. For the calculation of the collection area of the rooftop PV array, the combined dimensions of all arranged modules are selected. This is an approximate calculation of the area of 500 PV modules for the total 135 kWp size. Therefore, using (3), with $L_{PV} = 18.7m$, $W_{PV} = 56.65m$ and $H = 15m$, the collection area of the PV array $A_{D/PV} = 14203m^2$.

Fig. 8: Photograph showing the protruding roof section of the Genmin Laboratories

The same value for the annual lightning ground flash density in Johannesburg of 11.7 flashes/km^2 is used. Also, the structure is assumed to conform to the LV wiring standards given in SANS 10142-1 [13]. There are buried incoming power and telecommunication lines. There is also a special hazard present in terms of the level of panic due to the estimated number of 20 people inside the structure at any given time. The LPZs are designated much in the same way as for the residential structure where LPZ_1 is outside the structure and LPZ_2 inside the structure. The only consideration for the outside of the structure is the risk of economic loss. However, for the complete risk assessment, again the pertinent considerations for this medium-scale system are the risk of loss of human life and risk of economic loss. The main parameters used in the calculation of the risk constituents to determine the overall risk are indicated in Table VI.

Using the given parameters, along with the remaining required parameters, the risk of lightning damage to the structure is calculated. The results of the risk assessment are indicated in Table VII. The results of the risk assessment are also graphically illustrated in Fig. 9.

The results indicate that for a medium-scale rooftop PV system, there is a significant increase in both risk of loss of human life of 25.13% and economic loss of 72.62%. Due to the size of the rooftop PV array, the increase in risk of economic loss is more pronounced. The results indicate that this risk is below the threshold. However, due to the costs associated with the installation of this size PV system, protection is certainly a consideration. The risk of loss of human life is almost 17 times above the threshold. This is a significant risk factor. Therefore an LPS is certainly required for protection of the structure and PV system itself.

TABLE VI: Specifications of the Commercial Structure

Environment and structure		
Input parameter	*Symbol*	*Value*
Ground flash density (1/km^2/year)	N_G	11.7
Structure collection area (m^2)	A_D	16516
PV array collection area (m^2)	$A_{D/PV}$	14203
LPS installed (none)	P_B	1
Equipotential bonding (LPS - none)	P_{EB}	1
Power line		
Installation factor (buried)	C_I	0.5
Line type factor (LV)	C_T	1
Telecom line		
Installation factor (buried)	C_I	0.5
Line type factor (telecom)	C_T	1
PV 'line'		
Installation factor	C_I	1
Line type factor (LV)	C_T	1
Zone 1 (consists of rooftop PV array)		
Type of floor (concrete)	r_t	10^{-2}
Risk of fire (ordinary)	r_f	10^{-2}
Coordinated line SPDs (none)	P_{SPD}	1
Persons in zone (none)	-	0
Zone 2 (inside structure)		
Type of floor (ceramic)	r_t	10^{-3}
Risk of fire (ordinary)	r_f	10^{-2}
Coordinated line SPDs (none)	P_{SPD}	1
Persons in zone (20)	-	1

TABLE VII: Results of the lightning risk assessment for the commercial case study

		Structure	*Structure with PV*
Human life (R_1) $\times 10^{-5}$	LPZ_1	-	-
	LPZ_2	13.555	16.962
	Total	**13.555**	**16.962**
Economic (R_4) $\times 10^{-3}$	LPZ_1	-	0.0169
	LPZ_2	0.0694	0.1032
	Total	**0.0694**	**0.1201**

V. CONCLUSION

The investigation of practical case studies for residential and commercial rooftop PV installations is indicative of the lightning risk considerations for such installations. The risk of lightning damage to structures fitted with larger rooftop PV systems is more prominent due to the collection area of the PV array. There is no significant increase in risk for a structure fitted with a small-scale rooftop PV system. However, in terms of lightning protection, the investment of a PV system and the associated cost, warrants the installation of an LPS for the existing structure and for the PV system itself.

Lightning can cause significant damage to rooftop PV systems. Areas with favourable climatological conditions for PV energy generation, coupled with high lightning ground flash densities are prone to this damage. The expansive potential growth of PV systems worldwide and particularly on the African continent warrants the understanding of lightning risk and protection requirements for PV systems. The proposed framework will assist in the development of lightning protection standards for rooftop PV systems where the attractiveness of these installations for home owners, businesses and institutions in urban, suburban and rural areas is undoubtedly apparent.

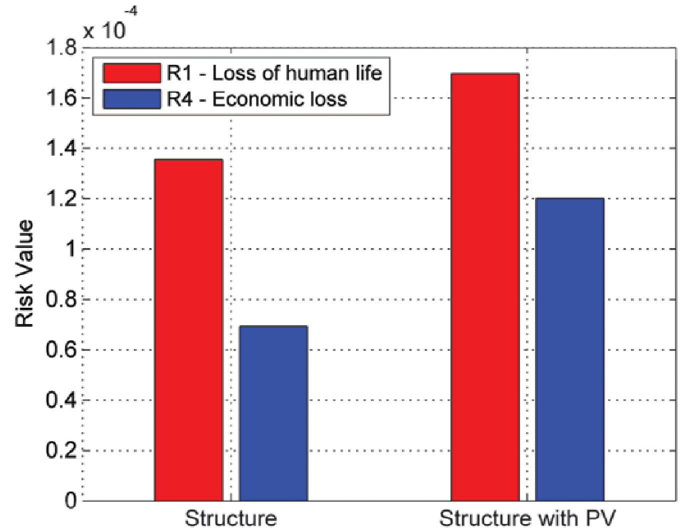

Fig. 9: Bar chart illustrating the results of the risk assessment for the commercial structure fitted with a rooftop PV system

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