THE ROOF COMES FIRST · WHITEPAPER

DC arcs as a heat source

How DC arc faults start, persist and end in rooftop PV

> **CORE PRINCIPLE**
> **The source must be characterised before its consequence can be assessed.**

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Use and scope. This paper reviews published and available evidence on DC arc faults in rooftop PV. It does not present new testing and is not a substitute for project-specific electrical, fire, roofing, insurance or legal advice. Test results, standards and approvals apply only within their stated scope. The responsible professionals and approving parties remain responsible for project-specific decisions.

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Contents

Author's perspective....3
Executive summary....4
1. Why DC arc faults need a fire-risk analysis....6
2. How DC arcs initiate....7
3. Where arcs occur in rooftop PV systems....9
4. What makes a DC arc stable....11
5. Duration: when an arc becomes a sustained source....14
6. How DC arcs extinguish....17
7. Source-side controls: detection and interruption....20
8. The source vector....23
9. What current testing demonstrates and what it does not....26
10. Implications....28
11. Conclusions....29
References....30
Research transparency....31
Appendix A: evidence map....32
Appendix B: electrical fault locations and mechanisms....34
Method and sources....35
REVISION HISTORY....36
The series....37

Author's perspective

This series is a synthesis of published research, fire tests, standards, approvals and insurer guidance on fire safety and rooftop PV, written from an explicit roof-first perspective: I look at the complete commercial roof system and the building beneath it rather than at individual product classifications. Within that perspective I summarise what the evidence shows, add my own technical analysis and, where relevant, propose design principles. Those proposals are marked as mine and kept separate from what has been demonstrated.

My background is in architecture and building engineering. Over the past three years I have discussed this subject with engineers, risk specialists, insurers and test institutes, and I have been involved in setting up and supervising fire-test programmes for AllShield's own roof systems. That experience shapes the questions I ask; the papers test those questions against external evidence. How the sources were selected, and what remains open, is described at the end of each paper.

These papers are prepared by Olivier Langejan as lead author with support from a small team. His own professional focus is building and roof design; specialist findings are drawn from the cited evidence, with AI assistance disclosed separately in Method and sources.
I am affiliated with AllShield, which develops BarrierSheet and other roof fire-protection solutions. That commercial relationship is relevant and is therefore stated explicitly. The analysis does not assume that an AllShield product provides the effects discussed. Where an AllShield product is discussed elsewhere in the series, its performance should be read only within the boundaries of the cited tests, approvals and roof assemblies.

This paper isolates the electrical source side of one part of the rooftop PV fire problem. It asks how DC arcs start, where they can occur, what allows them to persist, what causes them to extinguish and how detection and interruption change the source. It deliberately stops before asking what that source does to the roof. The formal output is a source vector that the companion paper, DC arcs at the roof-PV interface, takes as its input.

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Executive summary

CORE THESIS

A DC arc should be characterised as a source before its consequence is inferred. The same physical gap can behave differently in different PV circuits and a fixed test duration is not the same as a natural arc lifetime. This paper therefore ends with a source vector: the characteristics of the sustained thermal source that the electrical system can produce.

Why this paper

DC arc faults are one credible electrical ignition mechanism in photovoltaic systems. Series arcs are particularly relevant because PV installations contain many serial interfaces within modules, junction boxes, connectors, cables, terminals and switching equipment. Yet the existence of a fault does not by itself describe the fire exposure that may follow. A short unstable arc, a sustained series arc and a high-current parallel arc are materially different source conditions.

The purpose of this paper is deliberately narrow. It does not assess connector-to-roof clearance, roof membranes, insulation, protective roof layers or developed fire beneath PV. Those questions belong downstream in the source-pathway-receptor chain. This paper stays on the source side and asks what electrical and physical conditions determine whether an arc begins, persists and ends.

What the electrical evidence shows

The reviewed evidence supports series arcs as a credible fault configuration in ordinary PV systems and shows that they can arise at several serial interfaces rather than only at field connectors. Poor connections can first produce resistive heating. Continued degradation can then create a gap across which a series arc forms if sufficient voltage remains available. Parallel and earth-related arcs are less likely in the ungrounded European architectures described in the German guidance but can be more severe when they occur. [1][2][3][4]

Arc stability is a system property. DC has no periodic current zero and a PV generator is not an ideal fixed-voltage source. Available voltage and current, the current-voltage characteristic of the array, circuit topology, electrode geometry, irradiance and converter behaviour can all affect whether an established arc remains sustainable. Controlled research by EPRI, Putzke and co-authors and Li and co-authors demonstrates different aspects of that dependence. [1][5][6][7]

Duration is equally important. Fraunhofer ISE and TÜV Rheinland state that stable DC arcing can persist for up to several tens of minutes under suitable conditions, but the reviewed literature does not provide a representative statistical distribution for the natural duration of deteriorating rooftop connectors. Many experiments impose their own duration by switching the circuit or deliberately maintaining the arc. A test that runs for five minutes therefore demonstrates survival or controlled exposure for five minutes under the tested conditions. It does not by itself establish that five minutes is the natural upper bound of the fault. [1][5][6][7][8]

Source-side controls

Prevention reduces the probability that the fault develops. Monitoring and detection identify a developing fault and interruption changes the circuit so that the current sustaining a series arc is removed. IEC 63027 provides a standardised framework for series-arc detection and interruption; within its tested scope, a correctly detected and successfully interrupted series arc lasts seconds rather than minutes. That

changes the source substantially. It does not by itself address faults outside that scope, protection that is not present or not active, or material that ignited before interruption: interruption removes the arc, not necessarily a fire that has already started. [1][10][11][12][16][17][18]

Local connector containment is intentionally outside the scope of this paper. A connector enclosure can allow the arc to continue while restricting heat, flame or hot material from leaving the protected volume. In the source-pathway-receptor framework that is a pathway measure rather than a source-side control and it is therefore treated in the companion paper.

The source vector

The paper's formal output is a source vector with five components: intensity or thermal output; emission mode; source geometry and orientation; particle characteristics where relevant; and duration. The literature does not quantify every component for every realistic fault. Missing parameters remain visible rather than being inferred. That boundary matters because a source that has not been fully characterised should not be converted into a precise downstream exposure claim.

Main conclusion

A sustained DC arc should be treated not only as an electrical fault but as a potential external thermal source. Source-side protection can reduce the probability that the source develops and can shorten its duration to seconds when detection and interruption operate successfully. Where a component ignites before interruption, the source becomes a burning component rather than an arc. Where a residual sustained source remains relevant, its consequence depends on the pathway to nearby materials and on their response. Those downstream questions are the subject of the companion paper.

1. Why DC arc faults need a fire-risk analysis

An electrical fault is not yet a fire source

Rooftop PV is usually designed first as an electrical system. Better components, compatible connectors, correct installation, inspection and maintenance all reduce fault probability. Arc detection and interruption can terminate relevant electrical faults after they develop. These measures matter and nothing in this paper argues otherwise.

The analytical problem starts one step earlier than a building-fire conclusion. An electrical fault is not yet a defined external fire source. To understand what protection is required downstream, the fault first has to be characterised: what type of arc can occur, where it can occur, what sustains it, how long it can persist and what causes it to end. Only then is it possible to describe the source that a neighbouring material may face.

Peak temperature is not enough

Arc temperatures can reach several thousand degrees and that fact explains why arcs can damage conductors, insulation and surrounding materials. [1] Temperature alone is not a sufficient description of the hazard. Consequence also depends on how much energy is released, how that energy leaves the fault, the physical size and orientation of the source, whether hot or molten particles are generated and how long the source remains active.

The distinction matters because source intensity and source duration are not interchangeable. A high-current arc deliberately maintained for a short test period and a lower-current fault that persists for longer are different exposure histories. The reviewed literature does not establish one universal current-time combination that bounds every relevant PV series arc.

The chain addressed in this paper

This paper covers the source side of a source-pathway-receptor chain. It follows the sequence electrical fault → arc initiation → arc stability and persistence → interruption or extinction → source vector. Prevention, detection and interruption act on this source side. Separation, interposition and the receiving roof assembly are addressed in the companion paper.

The distinction is methodological rather than organisational. It prevents evidence about one stage from being silently converted into a claim about another. An experiment may demonstrate that an arc remained stable for a defined period without demonstrating what thermal exposure reached a particular surface. Conversely, a material may perform well under a fire test without that result defining the electrical source that produced the fire.

2. How DC arcs initiate

Why arcs deserve separate attention

An electrical arc is a conductive path through ionised gas between electrical conductors that are no longer connected in the normal way. In a PV installation, the resulting temperatures can damage conductors, insulation and surrounding materials. Fraunhofer ISE and TÜV Rheinland state that the greatest hazard potential within a PV installation arises from electrical arcs because the temperatures involved can reach several thousand degrees and can destroy surrounding material or initiate a fire. [1]

This is why the present paper focuses specifically on arcing while recognising that it is not the only possible route to electrical ignition. Resistive heating, for example, can precede arc formation and in some circumstances can itself provide sufficient thermal exposure for ignition.

Series arcs

The most relevant arc type in normal PV installations is the series arc. Fraunhofer ISE and TÜV Rheinland describe series arcs as substantially more likely than parallel arcs because a PV installation contains a very large number of serial electrical connections. These include cell connections within modules, connections between module components, module junction boxes, external junction boxes, plug connectors and connections associated with the inverter. [1]

A series fault can develop gradually. If an electrical interface is poorly made or deteriorates over time, its contact resistance can increase and generate local heating. Continued heating can degrade or remove conductive material until the connection begins to open. If sufficient voltage remains across that opening, current can continue through the ionised gap and an arc can form. The arc then becomes part of the existing string circuit rather than forming a conventional short circuit around it. [1]

Fraunhofer ISE and TÜV Rheinland also note that series arcs can be difficult to notice because the installation may appear to continue operating normally while the fault is present. [1] This suggests that such a fault cannot be assumed to present itself as a conventional overcurrent event.

Parallel and earth-related arcs

A parallel arc forms between conductors at different electrical potentials and can therefore have substantially more electrical energy available than a series arc. The German guidance nevertheless describes genuine parallel arcs as relatively unlikely in normal PV installations. PV cables are normally double insulated and a parallel fault generally requires damage to two conductors in close proximity together with the conditions necessary to initiate an arc. [1]

A related route can arise through multiple earth faults, but the inverter systems described in that guidance commonly use insulation monitoring to detect an initial earth fault before a second fault can develop into a more severe configuration. [1] The important point is therefore not that parallel or earth-related arcs can be ignored, but that the available guidance does not treat the different arc configurations as equally probable.

Fault development can change configuration

The arc categories are not necessarily isolated throughout the development of an incident. Fraunhofer ISE and TÜV Rheinland report that the destructive power can increase substantially when a series arc develops into a parallel arc, for example when an existing arc reaches neighbouring string conductors. [1] This does not mean that every series arc will make such a transition, but it indicates that the physical arrangement of conductors around an established fault can influence how the event develops. For a

commercial rooftop array, that possibility is relevant because multiple DC conductors can be routed in close proximity beneath or between module rows.

Heating can precede arcing

Arcing is also not necessarily the first stage of electrical deterioration. BRE identifies poor crimps, incomplete mating, incompatible connectors, loose terminals, moisture ingress and poor solder joints among likely causes of arcing. [2] In its separate discussion of resistive heating, BRE explains that increased electrical resistance can generate substantial local heat and can itself provide an ignition mechanism even before a fully developed arc exists. [2]

The physical sequence can therefore develop from increased resistance through local heating and material degradation to eventual separation and arc formation, but ignition does not necessarily have to wait until the final stage.

The source-side implication is that arc detection addresses only one part of the electrical deterioration sequence. A resistive connection can create substantial local heating before a mature arc signature exists. Any interpretation of arc-protection performance should therefore distinguish the fault mechanism that is actually within scope.

3. Where arcs occur in rooftop PV systems

A series arc is not the same thing as a connector arc

The conclusion that series arcs are the most credible arc configuration does not identify one component as the dominant source. A PV string is itself a chain of serial electrical interfaces, beginning inside the module and continuing through junction boxes, connectors, cabling, switching equipment and the inverter interface. The relevant question is therefore not simply whether connectors can arc, but where throughout that chain a poor or deteriorating electrical connection can develop.

Inside the PV module

The first serial interfaces already exist within the module. Individual solar cells are electrically interconnected by ribbons and other conductive connections, which ultimately connect to the module junction box. Fraunhofer ISE and TÜV Rheinland include cell connections, module connections and junction-box interfaces among possible locations for series faults. [1]

Laukamp and Bopp provide a useful field example. In an inspection programme covering approximately 7,100 modules from different manufacturers, six modules were found with a hot solder joint between cell and module interconnections. They note that, if additional conductive paths also fail, such a solder joint can open and an arc can develop. [4] The significance of this observation is not its frequency, which cannot be extrapolated to the wider PV population, but its location: a developing electrical fault can exist within the module itself before current reaches an external field connector.

Junction boxes and module interfaces

The module junction box introduces another group of electrical interfaces. It connects the internal module circuitry to the external DC cabling and may contain bypass diodes and associated connections.

Fraunhofer ISE and TÜV Rheinland include junction boxes and their electrical interfaces among relevant fault locations. [1] Historical French experience provides an independent example of why this component cannot simply be ignored. In an official response concerning Scheuten Multisol modules, the French government reported around thirty fires, according to the Fédération française des sociétés d'assurance, on rooftop installations using those modules. Defective connection boxes located on the rear of the modules were identified as the implicated component. [3]

This historical case does not establish that every incident involved a sustained electrical arc and it does not establish a present-day failure rate for modern module junction boxes. It demonstrates that a credible electrical ignition source can exist within the module assembly itself, outside the field connector.

Connectors

Outside the module, plug-and-socket connectors create another large population of serial electrical interfaces. Some are factory fitted to module leads and others are assembled, extended or terminated in the field. Poor crimping, incomplete mating, contamination, moisture ingress, mechanical loading and technically incompatible connector combinations are recognised fault mechanisms. BRE and Laukamp and Bopp both identify connectors as recurring locations of electrical faults, heating and arcing, with poor crimping, poor mating and cross-mating among the reported mechanisms. [2][4]

This makes connector-focused risk reduction technically rational. A commercial rooftop PV array can contain a large number of connectors. The point is not to minimise this risk. Connector faults deserve attention precisely because series arcs are the more credible arc configuration and connectors represent a substantial population of serial interfaces. The question is whether they represent the whole series-fault landscape. The available evidence does not support that simplification.

Cabling, switching and combiner equipment

Once current leaves a module connector it continues through DC cabling and, depending on system architecture, through extension leads, switching equipment, isolators, combiner boxes and other terminals before reaching the inverter. Each intentional interface in that series path can potentially become resistive if it is inadequately installed, becomes loose or deteriorates.

BRE's fire-investigation work records incidents involving connectors, DC isolators, cabling, combiner equipment, modules and inverters. [2] These historical UK data should not be turned into a universal ranking of current component risk because system architecture and installation practice differ by country, time period and application. The more defensible conclusion is simply that real electrical faults have been observed in several component categories rather than only at field connectors.

Continuous DC cabling is somewhat different because an intact cable does not contain an intentional contact interface. Mechanical damage, poor termination or interaction with adjacent conductors can nevertheless create fault conditions, while the routing of multiple cables can influence escalation if an arc develops nearby.

The inverter and the DC boundary

Connections on the DC input side of the inverter remain part of the string path and can therefore be relevant to series-fault analysis. Faults inside the inverter or on the AC side belong to a different part of the electrical system and often occur in a very different physical location.

Historical field data also include faults in inverters and AC-side components. Those data are useful as a reminder that electrical failures are not confined to one component category, but they should not be converted into a current international ranking because system architecture, installation practice and study populations differ. [4]

Historical system architecture affects interpretation

Historical forensic distributions also have to be read against the electrical architecture in which they were collected. NREL reports US evidence in which series arcs and ground faults accounted for many of the investigated events. Fraunhofer ISE and TÜV Rheinland describe a different European context in which ungrounded PV generators, protective insulation and earth- and short-circuit-resistant routing reduced some earth-related and parallel-fault mechanisms. [1][10]

The point is not that one dataset is right and another is wrong. They describe different systems and periods. A component or fault ranking can change when grounding topology, inverter architecture, connector practice and protective measures change. This paper therefore uses historical data to establish credible fault locations and mechanisms, not to create a universal present-day probability table.

Component statistics require caution

It is tempting to turn incident datasets into a ranked list of components. That would overstate what the available evidence can support. Historical German, UK and French information was collected in different periods, from different installation populations and using different investigation methods. System architecture and installation practice have also changed over time.

For this reason, this paper uses those datasets primarily to establish credible fault locations, rather than to construct a universal present-day ranking of components. This paper does not reconstruct precise component percentages from graphical data.

The source-side conclusion is therefore modest but important: credible arc and related fault locations exist at more than one serial interface. Connector faults are technically important, but the electrical source landscape is broader than the connector population alone.

4. What makes a DC arc stable

Why DC matters

A common way to visualise an electrical arc is as a discharge across a physical gap. That geometry matters, but it is not sufficient to explain whether a PV DC arc will continue or extinguish. The arc exists inside an electrical circuit and its stability depends on the interaction between that arc and the source supplying it.

One important difference from AC is the absence of a periodic current zero. In an AC circuit the current passes through zero every half-cycle, creating a recurring opportunity for the plasma channel to extinguish. In DC there is no equivalent periodic interruption. Fraunhofer ISE and TÜV Rheinland therefore state that a DC arc can remain stable for as long as sufficient voltage and current remain available to sustain it. [1]

That does not mean a DC arc necessarily continues indefinitely. An arc can extinguish when the electrical or physical conditions cease to support it. The point is that those conditions have to change; there is no periodic current zero doing that automatically.

The PV generator is part of the arc system

PV adds another layer because a photovoltaic generator does not behave like an ideal fixed-voltage DC source. Its available voltage and current are linked through the current-voltage characteristic of the array and vary with irradiance, temperature and the operating point imposed by connected power electronics.

Fraunhofer ISE and TÜV Rheinland describe how the PV-generator characteristic can allow an arc to remain stable under conditions different from those of a conventional DC source. The interaction between the source characteristic and the electrical characteristic of the arc can allow stable arcing at smaller contact separations than might be expected from a simplified fixed-voltage model. [1]

The physical gap therefore cannot be treated as an independent clock. Whether an arc survives as the gap, electrodes and surrounding materials change depends partly on whether the complete circuit can continue to provide conditions in which the arc remains sustainable.

What EPRI shows and what it does not

EPRI's 2018 experimental programme provides useful evidence of this system dependence, but its scope is very different from the rooftop series faults that are central to this paper. The experiments were conducted on an approximately 1 MWdc ground-mounted PV plant containing 171 parallel strings feeding two 500 kW inverters. The programme created arcs in calibration, combiner-box and inverter-cabinet configurations, with faults occurring between conductive rails or between conductors and grounded enclosures. These were therefore predominantly parallel- and ground-fault-type configurations rather than a series arc developing in a string connector. In some tests the arc current exceeded 1,000 A and reached approximately 1.4 kA. [5]

Those conditions are not representative of a series arc in an individual rooftop string connector. The numerical current levels, electrode separations and incident energies from the EPRI programme should therefore not be transferred directly to that scenario. The value of the work for this paper is narrower: it demonstrates how strongly DC-arc stability can depend on the surrounding electrical circuit, grounding arrangement and physical geometry.

During testing, the open-circuit array voltage was approximately 750 V and arcs could be sustained across gaps as long as approximately 25 cm in some configurations. Longer arcs became more likely to self-clear, while the EPRI summary reports that arcs in the tested combiner-box configuration did not self-

clear at gaps below approximately 5 cm. [5] One individual combiner-box test briefly extinguished and re-established during the event, a useful reminder that even within one configuration arc behaviour need not be perfectly steady. These dimensions belong to the high-current EPRI equipment and should not be read as universal extinction distances.

The programme also showed that grounding topology mattered. When the negative PV terminal was left floating, the enclosure could no longer provide the same return path and arcs became less likely to remain sustainable. In one inverter-cabinet test with a floating negative terminal, the arc self-cleared after approximately 0.25 seconds despite relatively tight bus spacing. [5] The relevance of this result is not the specific quarter-second duration, but the demonstration that changing the surrounding circuit topology can determine whether an arc remains stable at all.

The inverter influences the operating point

The role of the inverter also requires careful wording. EPRI found that the PV array remained the main continuing energy source during its DC arc tests. In the two tests conducted with an operating inverter, the inverter contribution was small but not zero. A brief capacitor-discharge current spike occurred during approximately the first 50 milliseconds after arc initiation and contributed around 12% of the total measured arc energy. After that initial transient, the continuing arc energy came predominantly from the PV array. [5]

The distinction matters because saying that the inverter "feeds" the arc can imply a second sustained energy source. A more accurate interpretation is that, apart from this brief capacitor-discharge contribution at initiation, the PV array remains the main continuing source while the inverter or converter can still influence the electrical operating point at which that source is used.

Converter control and MPPT can affect stability

Putzke and co-authors investigated this operating-point interaction in 2024 using standardised series arcs, an electrode arrangement based on IEC 63027 and a photovoltaic array simulator. Their work compared different converter-control strategies and found that control behaviour can influence whether an arc remains stable or self-extinguishes. Current- and power-based control could sustain arcs under lower-voltage conditions than simplified assumptions would predict. [6]

The experiment should not be confused with a naturally deteriorating rooftop connector. It used controlled electrodes and a simulated PV source specifically to study the underlying electrical interaction. Its relevance here is therefore not that it reproduces a field failure, but that it demonstrates experimentally that the same arc geometry can behave differently depending on the source curve and converter-control strategy.

Li and co-authors examined a related issue in 2020 using a small grid-connected PV system with a series arc in the DC circuit. Their work investigated the interaction between the arc and a perturb-and-observe maximum power point tracking (MPPT) algorithm. The authors noted that much previous PV arc research had concentrated on relatively short detection windows and that longer-term interaction between the PV system and an established arc had received less attention. [7]

Their experiments and modelling showed that the interaction works in both directions: the arc alters the electrical behaviour seen by the MPPT algorithm and the resulting operating-point changes can alter arc current. Under the conditions studied, a negative MPPT perturbation could reduce arc current. [7] This does not establish that MPPT always prolongs an arc or always makes it extinguish. Taken together with the 2024 work, however, it reinforces the same conclusion: arc stability is a property of the electrical system in which the arc exists, not of the air gap alone.

Stable also does not mean constant. Persistence does not imply constant current, geometry or thermal output: an EPRI combiner-box arc briefly extinguished and re-established during one test and the arc and the MPPT algorithm influenced each other in both directions in the work of Li and co-authors. [5][7] A sustained arc should therefore not be assumed to be a uniform source over its lifetime.

Taken together, the evidence does not support a universal gap-distance rule for arc persistence. Arc stability reflects the interaction between the discharge and the electrical system around it. Available source voltage and current, grounding topology, converter behaviour, electrode separation and evolving fault geometry can all matter. The next question is therefore time: for how long can those conditions remain capable of sustaining the source?

5. Duration: when an arc becomes a sustained source

Natural duration and experimental duration

Once an arc has formed, two time questions have to be kept separate. The first is the natural lifetime of the electrical fault if the circuit remains capable of supplying it. The second is the duration selected or imposed by an experiment. A controlled test can deliberately sustain an arc or terminate it after a selected interval. That makes the experiment reproducible, but the selected interval is not automatically the natural lifetime of the fault.

What published guidance says about duration

Fraunhofer ISE and TÜV Rheinland provide one of the clearest published statements on possible DC-arc duration in PV systems. Their German guideline explains that, unlike AC systems, PV DC circuits do not have a periodic current zero and that arcs can remain stable while sufficient voltage and current remain available. The authors add that this condition can persist "bis zu einigen zehn Minuten". [1]

The wording deserves care. The German expression is most naturally understood as up to several tens of minutes. The official U.S. Department of Energy translation renders the same passage as "up to some ten minutes", which is less precise in English. For this paper the German original is therefore treated as controlling. [1]

The duration statement itself should not be given more evidential weight than it has. The guideline is an extensive expert and research synthesis, but this particular duration statement is not presented there as the result of a cited experimental programme in which representative rooftop connector arcs were observed naturally burning for several tens of minutes. It supports the proposition that stable PV DC arcs are not inherently limited to a few seconds or a fixed short duration. It does not establish that a typical rooftop connector arc will persist for tens of minutes.

Experiments often determine their own duration

The EPRI programme discussed in Chapter 4 illustrates why test duration has to be interpreted separately from natural arc duration. Many of those experiments used a timing relay and DC contactor to terminate the circuit after approximately 0.5, 2 or 10 seconds. [5] Where an arc remained active until the contactor opened, the test demonstrated survival for that interval under those conditions. It did not reveal when the arc would eventually have extinguished naturally.

The same principle applies more broadly to controlled arc testing. Experimental control is necessary if tests are to be repeatable, safe and comparable. A researcher may deliberately establish an arc, control electrode spacing, regulate the electrical source or terminate exposure after a selected period. Those choices do not invalidate the experiment. They define what it has demonstrated.

Putzke and co-authors investigated standardised series arcs specifically to understand self-extinction and showed that the outcome depends on PV source characteristics and converter-control strategy. [6] Li and co-authors likewise found interaction between an established series arc and PV-system operating behaviour, while noting the comparatively limited attention given to longer-term interaction. [7] Neither study provides a universal maximum natural duration for a deteriorating connector in a commercial rooftop system. The literature reviewed for this paper therefore does not establish a single maximum time after which every relevant rooftop PV series arc can be assumed to have extinguished.

A deliberately maintained connector arc

The programme described in manufacturer technical note ARC002, commissioned by the manufacturer of a connector-containment enclosure and carried out on a flat-roof set-up at ZAG, provides a different example of controlled duration. The electrical source used a modified DC connector carrying 35 A. One side of the connector could be moved and the spacing was continuously adjusted so that the arc remained active during a five-minute test. [8]

For this paper the relevant point is the source condition rather than the performance of any downstream pathway or receiving-surface measure. The experiment demonstrates that a connector-based arc source could be deliberately maintained at 35 A for the full five-minute interval when geometry was actively adjusted to prevent extinction. It does not independently establish that a naturally deteriorating connector would hold the same geometry or remain active for exactly that period.

The technical note explains that five minutes was selected because the developers expected an arc under that 35 A source condition to have destroyed the connector and self-extinguished within that period. [8] That is a legitimate engineering rationale. It is nevertheless a rationale about expected natural extinction rather than a natural-extinction measurement produced by the test itself.

Intensity and duration are different source variables

The ARC002 programme also illustrates why intensity and duration should remain separate source variables. At 35 A, the experiment imposed a demanding electrical condition and deliberately maintained the arc for the chosen five-minute period. The current value describes part of the source condition. The five-minute interval describes the time for which that source was maintained. Neither variable by itself defines the other. For context, a 550 W module datasheet lists a maximum-power current of approximately 13 A under standard test conditions. [15] In a series string the current does not increase with the number of modules; a string of such modules operates at a current of that order. The 35 A condition therefore lies well above the STC maximum-power current of such a string. The comparison explains the test condition; it does not establish 35 A as a typical string current or as a universal worst-case arc current.

A test can therefore be conservative in one source variable without necessarily being conservative in another. Demonstrating one does not automatically establish the other.

Even where a lower-current arc produces lower instantaneous thermal output, it should not automatically be dismissed if it can persist for a different or longer period. If the electrical conditions allow the fault to persist for a different period, its exposure history will also be different. The literature reviewed here does not establish a universal relationship between arc current and natural duration from which one bounding current-time combination can be derived.

Why one current-time envelope cannot yet be assumed

A tempting simplification would be to combine current and time into one bounding source envelope. The reviewed literature does not support that step. Arc voltage, electrical operating point, geometry and the mode by which energy leaves the fault can change as a component deteriorates. Two arcs with the same current can therefore have different thermal outputs and different extinction behaviour.

The controlled studies also address different configurations. EPRI includes high-current parallel and ground-fault equipment. Putzke and co-authors use standardised electrodes with a PV simulator. Li and co-authors study a small system and a particular MPPT interaction. ARC002 deliberately maintains a connector arc by adjusting spacing. [5][6][7][8] These experiments are complementary, but they do not form one continuous current-time dataset from which a universal rooftop connector envelope can be calculated.

The appropriate output is therefore not one assumed worst-case pair of current and time. It is a source vector in which electrical intensity and duration remain separate and in which geometry, emission mode and particle production can also be represented. Chapter 8 formalises that handover.

What remains unknown about natural duration

Fraunhofer ISE and TÜV Rheinland allow for stable DC arcing over periods materially longer than a few seconds. Controlled work shows that persistence depends on source and circuit conditions. [1][5][6][7] At the same time, none of the sources reviewed here provides a representative distribution of the natural lifetime of real deteriorating rooftop connector arcs from which a universal maximum can be derived.

This is an evidence gap, not evidence that any particular short test duration is inadequate. A timed test should be credited for the duration it demonstrates under its stated conditions. The separate question is whether another body of evidence establishes that the same duration bounds the natural electrical fault. The literature reviewed here does not establish that proposition universally.

6. How DC arcs extinguish

An arc ends when the circuit can no longer sustain it

The previous chapter established that a fixed test duration is not the same thing as the natural lifetime of an electrical arc. The next question is therefore what actually causes an established PV DC arc to end.

At the most basic level, an arc extinguishes when the electrical and physical conditions can no longer sustain the conductive plasma path. That can happen in several ways. Current can be deliberately interrupted, the voltage required to maintain the arc can rise beyond what the source can provide, the circuit topology can change or the physical fault itself can evolve until a stable arc path no longer exists. These mechanisms are related, but they are not equivalent. Some are deliberately engineered protection functions. Others depend on how a damaged component happens to deteriorate during the event.

Designed extinction and uncontrolled fault development

Fraunhofer ISE and TÜV Rheinland describe several established techniques for extinguishing electrical arcs: increasing arc length, cooling the arc, applying pressure and dividing the arc into multiple shorter sections. These measures increase the voltage or energy required to maintain the discharge until the source can no longer sustain it. [1]

The context is important. In the Leitfaden these mechanisms are described in relation to switching and arc-extinguishing equipment, where geometry, materials and switching behaviour are deliberately designed and tested to interrupt the arc. Some of the same physical effects can occur naturally in a failing connector. As material burns or melts, the arc path may lengthen and cool and the electrodes may move apart. The difference is that this process is uncontrolled and depends on the construction of the component and on the particular way damage progresses during the fault.

A growing air gap is therefore a physically valid extinction mechanism, but not an independent timer that defines when every connector arc must end.

Active interruption of a series arc

A different mechanism is to remove the current electrically rather than wait for physical deterioration to change the arc. McCalmont's NREL report explains this clearly for a series arc. Because the arc lies within the intended current path, shutting down the inverter or opening the DC circuit causes the string current to fall to zero and the series arc to extinguish. [10]

This is the operating principle behind arc-fault detection combined with interruption. Detection identifies the abnormal electrical condition. Interruption changes the circuit so that the current sustaining a relevant series arc is removed. In source-vector terms, successful interruption truncates the duration of the source rather than waiting for the damaged component to reach natural extinction.

The distinction also explains why arc type matters. Johnson and co-authors experimentally examined series and parallel arc faults and found that opening a series-type interruption device in response to a parallel fault does not necessarily extinguish that fault and can alter the current flowing through the parallel arc path. [11] The appropriate interruption strategy therefore depends on the electrical fault configuration. This does not alter the earlier conclusion that series arcs are the more credible arc configuration in the European rooftop PV architectures described in [1]. It shows why an extinction mechanism demonstrated for one fault configuration should not automatically be generalised to every DC arc.

Topology can remove a sustainable arc path

EPRI provides another example of extinction by changing the surrounding circuit. As discussed in Chapter 4, its experiments concerned high-current parallel- and ground-fault configurations rather than representative rooftop connector series arcs. Nevertheless, they showed clearly that circuit topology influenced whether an established arc remained sustainable. [5]

When the negative side of the tested PV system was left floating, the grounded enclosure no longer provided the same return path. In one inverter-cabinet test the arc then self-cleared after approximately 0.25 seconds. [5] The specific time and current cannot be transferred to a rooftop connector, but the mechanism is relevant: the arc ended because the electrical conditions around it changed, not because a component reached a predetermined level of physical destruction.

Taken together with the NREL evidence, this separates two broad approaches. An arc can be ended actively, by deliberately interrupting or reconfiguring the circuit, or it can end passively, because the evolving physical and electrical conditions of the fault no longer support stable arcing.

Connector destruction is plausible but not a clock

A common engineering rationale is that a severe series arc progressively damages the connector. Polymer material burns or melts, conductive material erodes and the conductors eventually move sufficiently far apart that the arc voltage required to bridge the growing gap exceeds what the string can sustain. The arc then extinguishes.

Nothing in the evidence reviewed here makes that mechanism implausible. It follows directly from established arc physics: increasing the arc length can increase the voltage required to sustain the discharge. [1] The ARC002 technical note discussed in Chapter 5 uses essentially this reasoning when explaining why five minutes was selected as a plausible worst-case duration. [8]

The issue is therefore not whether connector destruction can result in self-extinction. The issue is whether destruction provides a sufficiently predictable relationship between physical degradation and time to electrical extinction to serve as a general design boundary.

BRE's investigations provide an important qualification. Investigators observed that metal contacts in DC connectors could remain mechanically engaged by friction even after the supporting plastic body had burned away. [2] Destruction of the polymer housing therefore did not necessarily result in immediate physical separation of the conducting contacts.

That observation has a narrow evidential meaning. BRE does not establish that an electrical arc then continued for a particular period and it does not show that connector destruction normally fails to produce separation. BRE also cautions that arc evidence found after a fire may have been created by the developing fire rather than having caused it. [2]

What the observation does establish is more limited: loss of the connector housing is not, by itself, proof that the conductive contacts must already have separated. A self-extinction argument based on connector destruction therefore contains several physical steps. The housing deteriorates, the conductive parts move relative to one another, the resulting electrical conditions become incapable of sustaining the arc and this sequence occurs before the continued exposure causes unacceptable consequences elsewhere. The literature reviewed here does not establish a universal time for that sequence.

Self-extinction and interruption are different claims

An interrupted arc ends because a protection function deliberately changes the electrical circuit and removes the conditions sustaining the fault. For a series arc this mechanism is well established and forms the basis of arc-fault circuit interrupter (AFCI) protection. [10]

A self-extinguishing arc ends because the evolving physical and electrical conditions around the fault cease to support stable arcing. Increased separation, cooling, changing geometry, loss of available source voltage or a change in circuit topology can all contribute. [1][5] These mechanisms are physically valid, but their timing depends on the actual fault and system.

Irradiance provides a broader boundary

PV generation also has a broader environmental boundary. The current available from a PV array depends on irradiance, so under normal operating conditions the available source current reduces as daylight disappears. This provides a natural daily limit to sustained PV generation.

That observation should not be confused with a useful short-duration extinction assumption. A daytime fault can begin hours before sunset and the underlying defect can remain present after generation has ceased. When irradiance returns, the same defect can again become electrically relevant. Daylight therefore provides a broad environmental boundary, not a reliable short-duration protection function.

Fault type and interruption architecture remain linked

Interruption evidence also has to remain attached to the fault configuration. A series arc lies in the intended current path and can be extinguished by removing that path. A parallel arc can remain connected across conductors after a series branch is opened and may therefore require a different interruption architecture. Johnson and co-authors demonstrate why a protective action suitable for one arc configuration should not be assumed to terminate another. [11] The two findings combine with Chapter 2: an established series arc can develop into a parallel arc when it reaches neighbouring conductors. [1] If that transition has occurred, the fault is no longer within the scope of an interruption that only opens the series path.

This is a source-side evidence boundary rather than a criticism of AFCI technology. A device can perform exactly as intended within its series-arc scope. The design question is whether the fault being considered is within that scope and whether the corresponding interruption changes the electrical circuit in the way required to remove the source.

The missing quantity is time to reliable extinction

For a connector expected to destroy itself and thereby terminate an arc, the key quantity is not simply the time required to damage the connector. It is the time required for that damage to create electrical conditions under which the arc can no longer remain stable.

Those moments need not coincide. BRE's observations demonstrate why the distinction matters physically: severe loss of polymer support does not necessarily prove that the metal contacts have already separated. [2] Conversely, in other fault configurations the contacts may separate quickly and the arc may extinguish much earlier.

This is not evidence that self-extinction is unreliable. It is evidence that component destruction alone is not a measured clock for arc extinction. The literature reviewed for this paper has not identified a representative distribution of time-to-separation or time-to-natural-extinction for real deteriorating rooftop PV connectors. That is the same evidence boundary identified in Chapter 5, now viewed from the physical extinction mechanism rather than from test duration.

The source-side question is therefore not merely which physical mechanism can end an arc. It is what mechanism is expected to end the fault in the system being considered and what evidence establishes when that mechanism will operate.

7. Source-side controls: detection and interruption

Prevention acts before the arc exists

Good component selection, compatible connectors, correct crimping and mating, appropriate cable routing, installation quality, inspection and maintenance all reduce the probability that the electrical deterioration described in Chapter 2 develops into a hazardous fault. The incident literature reviewed earlier provides good reasons for taking these measures seriously. [1][2][4]

Their function is preventive. They reduce the likelihood that a fault develops, but once an established arc exists they no longer determine whether that arc is detected or interrupted. That is not a weakness. It is simply the boundary of the function being provided.

What the current standard requires

IEC 63027:2023 is the current international standard for DC arc detection and interruption in PV systems. Its public scope covers test procedures for the detection of series arcs in PV circuits and the response times of equipment used to interrupt them, and it states its purpose as reducing the risk of igniting an electrical fire. [12]

Fraunhofer ISE took part in the standardisation work. It describes the test as using an electronic DC source as a PV simulator and as a more realistic representation of real operation than the earlier US approach. According to its summary of the test, a detector passes when it switches off in less than 2.5 seconds, with the arc energy in the range of 200 to 750 joules under the test conditions; automatic reconnection after a trip is permitted four times within 24 hours. Fraunhofer ISE also states that short switch-off times reliably prevent a fire from starting. [16] That statement is the institute's own assessment. This paper has not reviewed the full normative text and attributes these figures to the Fraunhofer ISE summary.

For the source vector, the implication is direct. Where a series arc within the tested scope is correctly detected and successfully interrupted, its duration is measured in seconds rather than minutes. That is a substantial change to the source and, for the faults it covers, it makes the uncertain natural lifetime discussed in Chapters 5 and 6 much less important. Compliance demonstrates this behaviour under the test conditions; it does not by itself fix the duration of every conceivable fault. The permitted automatic reconnection is recorded under the duration component in Chapter 8.

Detection and interruption are separate functions

Detection identifies an electrical signature consistent with arcing. It does not by itself remove the energy sustaining the arc. A second function must change the circuit. For a series arc, opening the relevant series path reduces the string current to zero and extinguishes the arc. [10] This is why detection and interruption are combined in an AFCI protection strategy.

Successful interruption acts directly on the source vector by truncating its duration. This is fundamentally different from a measure that allows the source to continue but restricts its transfer to surrounding material.

Fast interruption and material ignition

Whether a short source can still ignite adjacent material is a separate question from whether the arc is interrupted. Sandia National Laboratories examined this for polymers commonly used in PV components. Experimental work with low-power arcs of 100 to 300 W close to polycarbonate, PET and nylon 6,6 noted

that UL 1699B tested AFCI devices only at arc powers between 300 and 900 W, while arcs of lower power can also create fires, and recommended trip times below 2 seconds. [17] A later modelling study, validated against 100 W and 300 W experiments, concluded that the maximum trip times required by UL 1699B are sufficient to suppress arcs of 100 to 1,200 W before fire initiation. [18] An earlier Sandia model of a corroded solder connection at a bypass diode predicted ignition of adjacent polymer near the diode and junction box within less than 0.1 seconds. [19]

These results are not necessarily contradictory, but neither are they directly comparable. They describe different geometries, materials and source conditions and the 0.1-second figure is a model result for one specific configuration, not a general ignition time for PV components. Taken together, they support the effectiveness of fast interruption under the conditions studied, while showing that the outcome depends on the ignition environment: geometry, heat transfer, material, fault location and available power.

Interruption removes the electrical arc. It does not necessarily remove a material fire that started before interruption. If ignition has occurred and the material continues to burn, the source is no longer an electrical arc but a burning component, which lies outside what electrical interruption can address. Chapter 8 records this change of source.

Why detection performance is a system claim

Earlier detector research showed why detection performance has to be demonstrated rather than assumed. The Fraunhofer/TÜV Leitfaden notes that arc location, cable length, inverter interference and switching transients can attenuate or mask the arc signature and that false trips can lead users to bypass protection. [1] Sandia's 2011 testing across module technologies, inverters and layouts found that system noise shapes the environment in which detection operates, while the prototype detector was generally stable and certain frequency ranges distinguished normal operation from controlled arcs. [13] A 2012 Sandia study showed that an arc signature on one string can propagate to a parallel string and cause AFCI devices on both strings to respond, primarily a nuisance-trip and fault-localisation issue. [14] Johnson and co-authors showed that series and parallel arc signatures can overlap and that a protective action suitable for a series arc does not necessarily extinguish a parallel arc. [11]

Most of this research preceded the current standard. It is cited here not as evidence that present-day detectors are unreliable, but for the principle it established: detection performance is a property of a detector within a defined electrical system. Compliance with a series-arc standard demonstrates performance within that scope. It does not by itself demonstrate performance for parallel arcs, for a series arc that has developed into a parallel arc (Chapter 6) or for an installation configuration outside the tested scenarios. [11][12]

Monitoring before an arc exists

Arc detection acts once an arc signature exists. Chapter 2 showed that a deteriorating connection can produce substantial resistive heating before that point. [2] Some module-level power electronics now monitor temperature at connector locations and can stop power flow when abnormal heating is detected. [21] This can provide an additional means of identifying abnormal heating before an arc develops, within the locations and operating conditions covered by the monitoring system. Other interfaces in the series chain, such as module-internal connections, unmonitored field connectors and terminals in switching equipment, remain outside that coverage unless they are separately monitored.

Implementation

The fourth evidence-boundary question in Chapter 9 asks whether a protection function was actually present and operating. For AFCI this question has four layers that should not be conflated: whether arc

protection is required, whether the installed equipment provides it, whether it is activated and configured and whether it performs as tested in the installed system.

In 2023, Fraunhofer ISE noted that manufacturers in the European market offered arc detectors on a voluntary basis. [16] Inverter documentation shows that arc-fault protection may need to be activated and that restart behaviour after a trip is a configuration choice. [20] Publication of IEC 63027 in 2023 also does not mean that installations commissioned earlier were tested to it or have been upgraded.

None of this diminishes the technology. It means that the duration benefit described above should be credited to an installation in which all four layers are established, not assumed from the availability of the technology.

Source-side controls in the source-pathway-receptor model

Within the source-pathway-receptor framework, prevention, monitoring, detection and interruption belong on the source side. Prevention reduces the probability that a source develops. Monitoring and detection identify a developing fault. Interruption modifies the electrical circuit and can shorten or terminate the duration of a relevant series arc.

A connector enclosure or other local containment device belongs elsewhere in the model. It can leave the electrical source energised while limiting the transfer of heat, flame or particles out of the protected volume. It is therefore treated as interposition in the companion paper rather than as a source-side control in this paper.

The practical question is therefore not whether AFCI is effective; within its tested scope it is designed to shorten the source to seconds. The questions are whether the fault being considered lies within that scope, whether the protection is present and operating in the installation and whether anything has ignited before interruption takes place. Where a fault lies outside that scope, the residual source has to be characterised rather than assumed away.

8. The source vector

Why a source vector is needed

The preceding chapters establish that the phrase 'DC arc' is too coarse to function as a complete fire-source description. Two arcs can differ in electrical power, spatial form, emitted heat, particle production and duration even when both are described by the same fault category. The companion paper therefore needs a structured handover rather than a single temperature or a single current value.

This paper uses the term source vector for that handover. The vector is not a claim that every component can always be measured precisely. It is a checklist of the variables that should be known, estimated or explicitly marked unknown before downstream exposure is inferred. The same five characteristics can describe successive heat sources within one event: the electrical arc and, where ignition occurs before interruption, the burning component that follows it.

1. Intensity or thermal output

The first component describes the magnitude of the source. Electrical current alone is not a thermal-output measure, but current and voltage help define the electrical conditions available to the arc. EPRI demonstrates that very high current arcs in large PV equipment are materially different from series arcs in an individual string. The 35 A ARC002 test provides another defined electrical condition, but it should not be converted into a universal rooftop arc intensity. [5][8]

Where direct calorimetric or heat-flux measurements are unavailable, the limitation should remain explicit. Describing a test as demanding because of current does not by itself quantify radiant, convective or particle energy delivered to a separate surface.

2. Emission mode

The second component describes how energy leaves the source. Relevant modes can include direct flame or plasma contact, radiant heat, convective heating and hot or molten material ejected from the failing component. The same fault can involve more than one mode at the same time. The electrical literature does not always quantify their relative contributions.

This component is the first point at which the source vector prepares the pathway analysis. This paper records what the source can emit. The companion paper asks how much of that emission reaches the primary receiving surface after distance, orientation, interposition and, for particles, trajectory factors such as initial direction, gravity and wind are considered.

3. Source geometry and orientation

The third component describes the physical form and direction of the source itself. Arc length, electrode spacing, conductor orientation and movement can influence stability. They can also affect the direction in which plasma, flame or hot material leaves the fault. Controlled arc programmes often stabilise or adjust geometry to answer a repeatable laboratory question. That geometry should therefore be recorded rather than treated as background detail.

A source geometry used in a standardised electrode rig is not equivalent to a degrading field connector. Likewise, dimensions observed in high-current EPRI equipment should not be transferred to a string connector. Geometry is part of the source definition and of the evidence boundary. [5][6]

4. Particle characteristics where relevant

A failing electrical component can eject or drop heated material. Where that occurs, particle temperature, size, mass, composition, velocity, direction and persistence may become relevant source characteristics. The evidence reviewed for this paper does not provide a complete quantitative particle distribution for realistic PV connector faults. That absence should be carried forward as uncertainty rather than filled with an assumed value.

The maintained connector tests provide qualitative evidence that hot material can accompany a connector arc. [9] The companion paper considers the pathway of such material. This paper records only that particle emission can be part of the source vector and that the available evidence is incomplete.

5. Duration

Duration is the fifth component and it is not secondary to intensity. An arc that is actively interrupted has a different source history from an arc that persists until changing geometry or source conditions cause self-extinction. A laboratory arc deliberately maintained for a selected interval has another source history again.

The reviewed evidence does not justify assigning one universal maximum duration to all relevant PV series arcs. The vector should therefore contain the duration actually demonstrated for the condition being discussed and should identify separately whether that duration was natural, imposed by test termination or maintained deliberately. [1][5][6][7][8]

Duration should also record whether the source was a single event or a sequence of events. Where protection permits automatic reconnection after a trip, as IEC 63027 does within defined limits [16], a fault that has not been physically removed can be re-energised and interrupted again. Each event may be short, but the exposure history then consists of repeated events, separated by intervals in which the surrounding material may or may not cool.

When the source changes character

The five components apply to each heat source in the sequence, as noted at the start of this chapter. Chapter 7 showed that fast interruption can prevent ignition of adjacent polymers under the conditions studied and that the outcome depends on geometry, material, fault location and available power. [17][18][19] Where ignition occurs before interruption, the source changes character. The arc ends when the circuit is opened; a component that has ignited and continues to burn becomes a source in its own right, whose intensity, emission mode, geometry, particle production and duration are governed by the material and its surroundings rather than by the electrical circuit.

This transition belongs to the source characterisation, not to the pathway or the receptor. The vector should therefore state which source it describes: the arc, a burning component after interruption, or both in sequence. Successful interruption bounds the duration of the first. It does not by itself bound the second.

Unknown components remain part of the result

A source vector does not become invalid because one component is unknown. The opposite is true: explicitly marking a parameter as unknown prevents the downstream analysis from acquiring false precision. For realistic deteriorating connectors, the reviewed literature is stronger on electrical current, voltage, stability and duration than on quantitative radiant fractions or particle distributions.

Where a study reports only electrical conditions, the downstream analysis should not invent a heat flux at the receiving surface. Where hot material is observed but particle size or temperature is not measured, the particle pathway can be recognised qualitatively while the missing characteristics remain an evidence

gap. This treatment keeps the distinction between what has been demonstrated and what is physically plausible visible throughout the chain.

The handover to the companion paper

> **SOURCE VECTOR**
> **Intensity or thermal output + emission mode + source geometry and orientation + particle characteristics where relevant + duration.**

The companion paper takes this source vector as its input, including the distinction between an electrical arc and a burning component where that distinction applies. It does not reopen the electrical physics unless a source parameter is missing or uncertain. It asks how pathway geometry, separation and interposition modify the exposure that reaches the first surface of the roof assembly and how the receptor responds at that boundary.

9. What current testing demonstrates and what it does not

Evidence should stay attached to its test question

Controlled arc research is valuable because it isolates variables that are difficult to observe in real incidents. Its strength is also its boundary. Standardised electrodes, simulated PV sources, high-current equipment or deliberately adjusted connector gaps answer different questions. A result should therefore be carried forward with the source configuration that produced it.

The same discipline applies to time. Where a contactor ends a test, the experiment establishes source behaviour until interruption. Where researchers continuously adjust electrode spacing to maintain an arc, the experiment establishes behaviour under deliberately maintained geometry. Neither condition is a measurement of the uncontrolled natural lifetime of a deteriorating connector unless the study was designed to observe that quantity.

Evidence status

Statement	Status	Boundary
Series arcs are a credible PV fault configuration and can originate at multiple serial interfaces.	DEMONSTRATED	Supported by guidance, incident investigation and field evidence. It does not establish a current component failure ranking.
Arc stability depends on the wider electrical system rather than on gap distance alone.	DEMONSTRATED	Supported across guidance and controlled experimental work. Exact numerical thresholds remain configuration-specific.
A series arc can be extinguished by active electrical interruption.	DEMONSTRATED	Applies when the relevant series path is successfully interrupted. Other arc configurations can require different interruption strategies.
Under IEC 63027 test conditions, a compliant device interrupts a correctly detected series arc within seconds.	DEMONSTRATED	As tested. Performance documented under standardised test conditions for series arcs, as summarised by Fraunhofer ISE; the full normative text was not reviewed. Field performance requires the protection to be present, activated and configured in the installation.
Physical connector destruction can cause natural self-extinction.	PHYSICALLY SUPPORTED	Consistent with arc physics and component degradation, but the reviewed literature does not establish a universal time to reliable extinction.
One universal maximum natural duration exists for relevant rooftop connector arcs.	UNKNOWN	No representative natural-duration distribution was identified.
One current-time combination bounds the thermal source for all relevant PV arcs.	UNKNOWN	The reviewed literature does not establish such a universal relationship.

Statement	Status	Boundary
Interruption within those limits prevents ignition of adjacent materials in every relevant configuration.	UNKNOWN	Sandia results support prevention under the conditions studied; a separate model predicts ignition within 0.1 s for one bypass-diode configuration. The outcome depends on geometry, material, fault location and power.
The complete source vector is quantified for realistic deteriorating connectors.	UNKNOWN	Several components are only partially described, especially emission fractions and particle characteristics.

The four evidence-boundary questions

Four questions from the previous integrated paper remain useful as an evidence test beneath the source-pathway-receptor framework: location, duration, mechanism and implementation. Where is the fault? For how long was the source observed or controlled? Which electrical mechanism was created? Was the protection function actually present and operating in the configuration being discussed?

These questions do not form a second physical model. They are a method for checking the scope of an evidence claim. Residual uncertainty begins where the demonstrated scope of that claim ends. That does not mean conditions outside the test are dangerous. It means the evidence no longer supports the same statement without additional justification.

10. Implications

Prevention remains the first layer

Good component selection, connector compatibility, installation quality, inspection and maintenance remain the preferred way to reduce the probability that damaging electrical deterioration develops. The existence of residual source uncertainty is not an argument for accepting avoidable faults.

Residual arc risk is not conceptually zero

The reviewed evidence supports neither a claim that every relevant fault will be prevented nor a claim that every established arc has the same natural duration. Source-side design should therefore distinguish probability reduction from consequence assumptions.

Detection and interruption act on the source

Where the relevant series arc is successfully detected and interrupted, the duration component of the source vector can be reduced to seconds. That can make uncertain natural self-extinction much less important. The benefit remains conditional on the fault being within the demonstrated electrical scope and on the protection being present and active in the installation. Fast interruption shortens the electrical arc even where material has already ignited; what it cannot do is end a material fire that started before interruption. That fire is a separate source, described in Chapter 8. This conclusion does not depend on any shortcoming of arc-fault protection technology.

Consequence limitation is a separate design objective

> **Where arc initiation cannot be reduced to zero probability, limiting the consequences of a sustained arc becomes a separate design objective.**

That objective is downstream from this paper. It should not be solved here by assuming a connector clearance, an enclosure or a roof construction. This paper stops when the residual source has been characterised as far as the available evidence permits.

Handover

The output of this paper is therefore the source vector: intensity or thermal output, emission mode, source geometry and orientation, particle characteristics where relevant and duration. The companion paper uses the same terms and asks what exposure that source imposes at the roof-PV interface.

11. Conclusions

1. Series arcs are a credible PV fault configuration because serial interfaces are distributed throughout the DC circuit. Connector faults are important but do not represent the complete series-fault landscape.
2. DC-arc stability is a system property. Available voltage and current, PV source characteristics, circuit topology, converter behaviour, electrode geometry and fault evolution can all influence whether an arc remains sustainable.
3. Experimental duration and natural arc lifetime are different quantities. A test demonstrates the duration for which the source was observed, maintained or controlled under the tested conditions. It does not automatically establish a universal natural-duration boundary.
4. Active interruption and natural self-extinction are different extinction mechanisms. Successful interruption deliberately changes the circuit. Natural extinction depends on the evolving physical and electrical conditions of the fault.
5. Prevention reduces the probability that a source forms, monitoring and detection identify a developing fault and successful interruption can shorten a series arc to seconds. These controls should be assessed within the electrical scope for which their performance has been demonstrated and in the installation as actually configured.
6. Interruption removes the electrical arc but not necessarily a material fire that started before interruption. The source vector should therefore state whether it describes the arc, a burning component or both in sequence. This conclusion does not depend on any shortcoming of arc-fault protection.
7. A sustained DC arc should be treated not only as an electrical fault but as a potential external thermal source described by a source vector. Its downstream consequence depends on the pathway to and the response of nearby materials, which are addressed in the companion paper.

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Research transparency

Professional relationship

I am Chief Commercial Officer of AllShield, which develops roof fire-protection solutions for commercial buildings. That affiliation is stated because it influences the wider questions explored in this series. No AllShield product is evaluated in this paper. This paper is limited to published and available evidence on DC arc initiation, stability, duration, extinction, detection and interruption.

Appendix A: evidence map

Source	Evidence type	What it supports	Important boundary
[1] Fraunhofer ISE / TÜV Rheinland	Research synthesis, experiments and guidance	Arc types, fault locations, DC stability, duration statement, detection issues	Historical German context; some statements are guidance rather than direct experiment; German original controls where translations differ.
[2] BRE	Incident investigation and technical analysis	Connector and component faults, resistive heating, connector contact behaviour	Historical UK dataset; post-fire arc evidence requires caution.
[3] French Assemblée nationale	Official incident response	Historical module junction-box fire experience	Product-specific historical case; not a current failure rate.
[4] Laukamp & Bopp	Historical field and damage analysis	Multiple electrical fault locations and mechanisms and component categories	Historical dataset; not current commercial-rooftop probabilities.
[5] EPRI	Controlled experimental research	System and topology dependence, high-current DC arcs, imposed test duration	Predominantly high-current parallel and ground-fault equipment; not a representative string-connector series arc.
[6] Putzke et al.	Controlled experimental research	Converter-control influence and self-extinction	Standardised electrodes and PV simulator.
[7] Li et al.	Modelling and experiment	MPPT and arc interaction	Small controlled system and specific MPPT method.
[8] ARC002	Third-party laboratory testing commissioned by manufacturer; manufacturer technical note	Maintained 35 A connector arc for five minutes; defined source condition	Test geometry was actively adjusted; five minutes is a demonstrated maintained exposure, not a measured universal natural lifetime.
[9] Tan / Burning Matters	Interested secondary source	Qualitative report of hot material associated with connector arc testing	Secondary account; used cautiously.
[10] NREL / McCalmont	Research and development report	Series-arc interruption and fault locations	Historical US architectures and data.
[11] Johnson et al. 2012	Controlled experimental research	Difference between series and parallel arc interruption	Test configurations are not equivalent to all present-day systems.
[12] IEC 63027 public scope	Normative scope information	Series-arc detection and interruption test scope	Full standard not reviewed for every detailed claim.
[13] Sandia 2011	Controlled detector testing	Detection capability, noise and nuisance-trip challenges	Prototype device and test-specific conditions.
[14] Sandia 2012	Controlled detector testing	Crosstalk and nuisance-trip behaviour	Primarily a fault-localisation and nuisance-operation issue.

Source	Evidence type	What it supports	Important boundary
[15] Jinko Solar datasheet	Manufacturer product data	Typical single-module maximum-power current, for context on the 35 A test condition	One module type at standard test conditions; not a representative string-current survey.
[16] Fraunhofer ISE 2023	Press release by an institute involved in the standardisation work	IEC 63027 test criteria and reconnection limits; voluntary offering of arc detectors in the European market in 2023	Summary of the test, not the normative text; market statement dated 2023.
[17] Armijo et al. 2014	Controlled experimental research	Ignition relevance of low-power 100-300 W arcs; recommended trip time below 2 s	Three polymers and specific test geometries.
[18] Armijo et al. 2016	Experimentally validated modelling	UL 1699B trip times sufficient to suppress 100-1,200 W arcs before ignition	Modelled configurations; relates to UL 1699B rather than IEC 63027.
[19] Bower et al. 2012	Finite element and analytical modelling	Possible ignition of polymers near a bypass diode within 0.1 s	One modelled configuration; not a general ignition time for PV components.
[20] SMA	Manufacturer documentation	AFCI activation and restart options	One manufacturer; settings vary by product and firmware.
[21] SolarEdge	Manufacturer documentation	Connector temperature monitoring before an arc develops	Manufacturer description; coverage limited to monitored locations; performance not independently reviewed here.

Appendix B: electrical fault locations and mechanisms

Location or mechanism	Evidence	Relevance to the source analysis
Internal cell or module interconnection	[1][4]	Serial interface inside the module; can develop resistive heating and series arcing.
Module junction box	[1][3][10]	Contains serial interfaces between module circuitry and external DC cabling.
Field or factory connector	[1][2][4][10]	Large distributed population of serial interfaces with recognised fault mechanisms.
DC terminal or switching interface	[1][2][10]	Intentional series connection that can become resistive if poorly installed or degraded.
DC cable damage or termination	[2][10]	Cable damage or poor termination can create fault conditions even where no normal connector interface exists.
Parallel or earth-related arc	[1][5][11]	Different electrical configuration, source severity and interruption behaviour.
Resistive heating before arcing	[2]	Can create hazardous local heating before a mature arc signature is present.

Method and sources

This is a targeted inventory and synthesis of identified knowledge, updated through the checks documented for 1 November 2026. It does not claim exhaustive coverage of the latest literature. Source findings, author analysis and practical design proposals remain distinct. The author endorses the conclusions within these evidence boundaries.

Authorship and contributions

Olivier Langejan is the lead author, supported by a small team. His professional focus is building and roof design. The papers synthesise the cited research, standards and test evidence; specialist fire-science and electrical findings are attributed to those sources rather than presented as expertise personally established across every discipline. The author endorses the synthesis and its stated limits. AI assistance is described separately below.

Scope and selection

This paper synthesises the intensity, duration and persistence of DC arcs as initiating heat sources. Controlled arc studies, technical guidance and source-specific test notes are included. Deliberately maintained laboratory arcs are distinguished from natural field duration. Developed roof fires and comparisons of commercial mitigation products are outside the principal question.

Sources and dates

The evidence base is the research, standards, approval documents, technical guidance and incident material identified in the references. This is a targeted narrative synthesis, not a systematic review. English-language sources and relevant Dutch or German material are included where cited. The original search dates and a complete search log are not available in the retained publication record, so no reconstructed search period or exhaustive publication cut-off is asserted. Sources retain their individual publication dates. The present editorial and targeted source checks were completed on 1 November 2026.

Publication range

Publication dates and editions are identified for the individual references. This targeted synthesis does not claim exhaustive chronological coverage or a reconstructed complete search period.

Verification

This revision checked the requested wording against the source papers and carried out targeted primary-source checks for the additions and source corrections identified in its revision history. It is not a new claim-by-claim audit of the entire paper. References identify primary documents where available; secondary accounts and access limitations are identified where material. Author interpretations and design proposals do not acquire test or approval status.

Known gaps

No representative field distribution of natural arc duration was identified in the sources reviewed. Controlled test duration is not a measured natural maximum.

AI-assisted research and writing

Artificial intelligence was used to help identify and locate technical literature, compare findings across sources, analyse evidence boundaries, organise the argument and assist with drafting and editing. AI-generated summaries were not treated as technical evidence. The selection of sources, interpretation of the evidence, conclusions and final wording remain the responsibility of the author.

Updates

New research, test results, incidents and regulation may lead to new versions. Editorial corrections and technical additions are identified separately in the revision history. Missing sources and evidence that challenges a conclusion are welcome.

REVISION HISTORY

Version	Date	Changes
1.0	21 October 2026	First published version. Status labels aligned with the two-axis evidence model of What does a fire test actually prove?.
1.01	1 November 2026	Editorial corrections: reframed as a roof-first knowledge synthesis; shortened the author perspective, added method and source limitations, labelled author interpretations and corrected the requested wording and transparency statements. Technical additions and source checks: No new fire-performance claims or tests.
1.02	1 November 2026	Method and sources and series overview: clarified synthesis status and description of the risk-model companion. No new DC arc duration, detection or interruption result introduced.
1.03	1 November 2026	Ch. 9: IEC 63027 evidence status normalised to DEMONSTRATED with the as-tested boundary. Appendix A: commissioned laboratory testing described as third-party. Authorship and expertise scope added.

THE SERIES

The roof comes first is a synthesis of knowledge on fire safety and rooftop PV from a roof-first perspective, by Olivier Langejan. Each paper stands on its own; together they follow one line of thought.

At the time of this version, the series consisted of:

Paper	For	In one line
Rooftop PV on existing commercial buildings	Asset owners, developers, project teams	A decision framework for resolving roof constraints before the PV investment is committed.
Rooftop PV on new commercial buildings	Developers, architects, project teams	Designing the roof and PV as one system from the start.
The economics of the rooftop PV decision	Asset owners, CFOs, risk managers	Probability, consequence and lifecycle cost from the asset owner's perspective, including Business Interruption.
From risk models to design requirements	Risk engineers, insurers, designers	An application of five established risk frameworks to consequence-limiting design for roofs with PV.
Beyond flame spread	Risk engineers, insurers, fire engineers	How far a rooftop PV fire can travel into the roof before it becomes a building loss, and what a separation layer changes.
What does a fire test actually prove?	Insurers, risk engineers, specifiers	What a fire test result does and does not demonstrate about a real roof with PV.
DC arcs as a heat source (this paper)	Insurers, risk engineers, PV designers	How DC arc faults start, persist and end in rooftop PV.
DC arcs at the roof-PV interface	Insurers, risk engineers, PV and roof designers	What determines roof exposure to a sustained DC arc and what current evidence shows about measures to limit it.
How much does PV clearance actually solve?	Insurers, risk engineers, PV designers, asset owners	What module-to-roof clearance does and does not demonstrate about the roof beneath it.
What if the PV panel could not burn?	Asset owners, risk engineers, insurers, PV designers	What a lower-combustibility PV module does and does not change for the roof beneath it.
What does an inspection actually prove?	Insurers, risk engineers, asset owners, inspectors	What inspection can establish, what it cannot and what still protects the roof when a fault is missed.

All papers and their latest versions: allshield.com/en/olivier-langejan

Comments, corrections, missing sources, evidence that contradicts a conclusion and field experience are welcome at ol@allshield.com. Relevant input is used in future versions. To be notified of new papers and versions, send a short email to the same address.

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