Rooftop PV Systems and Firefighter Safety

FINAL

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1 EXECUTIVE SUMMARY

In an effort to address the safety of firefighters performing operations at buildings with rooftop photovoltaic (PV) arrays, the 2014 edition of the National Electrical Code (NEC) included requirements for the first time for "rapid-shutdown" functionality: the ability to effectively de-energize specific PV system circuits that would otherwise remain energized by the sun after utility power is cut to the building. The 2014 requirements affect circuits outside the boundary of the PV array, but the first draft of the 2017 NEC extends that requirement to circuits inside the array, and is worded as an effective mandate for products incorporating disconnecting devices on every PV module. There is considerable concern in the PV industry over potential unintended negative consequences of such a mandate and for the lack of fact-based objective requirements that can serve as a basis for developing appropriate solutions.

This paper summarizes findings from a DNV GL study of firefighter rooftop operations, the hazards they may encounter when working around PV arrays, and means in which electrical hazards in particular can be mitigated or substantially reduced. The study included three major tasks: 1) a review of relevant publications focused on firefighting issues specific to PV, including tests performed in the U.S. and Germany; 2) in-depth interviews with firefighters discussing their rooftop operations, concerns and decision making processes with respect to PV; and 3) a Failure Mode and Effects Analysis (FMEA) based evaluation of various methods of shock-hazard reduction.

Some of the essential findings include the following:

1. Recently revised building codes mandating enhanced access around rooftop PV arrays represent a significant improvement and give firefighters more opportunity to carry out vital rooftop operations. However, their physical presence can still impede specific operations and will continue to impact the tactical decision making process of firefighters at the scene of a building fire.
2. UL testing has demonstrated effective methods of safely fighting fires involving PV arrays. It also demonstrates that there are currently no practical means of entirely eliminating shock hazard in arrays, particularly given uncertainties of failure or damage to components not typically used for safety measures.
3. A joint PV and fire industry study conducted in Germany recommended against requiring module level electronics because of reliability concerns and the potential to create a false sense of security. Instead, safe boundaries and firefighting tactics are emphasized.
4. DNV GL concludes that further electrical protection measures should be pursued within the array boundaries to reduce the risk of accidental shock and to improve operational decision-making, but not to serve as a rationale for intentional interaction. Firefighter training should emphasize this point.
5. The FMEA evaluated mitigation options against practical scenarios in which personnel may be exposed to electrical shock hazards. Module level control, multiple-point disconnection of circuits from each other and ground, and solutions that limit or protect access to circuits all scored similarly as potentially effective measures to reduce the shock hazards within arrays. Further testing and analysis is recommended to develop more concrete conclusions.
6. The study concludes that 1) revisions to the electrical code should include criteria for reducing the shock hazard while avoiding the prescription of specific product solutions; and 2) the analysis framework described is recommended as a model in the development of appropriate safety standards.

2 INTRODUCTION

The U.S. has seen tremendous growth in solar photovoltaic (PV) power system installations, and as part of that a proliferation of rooftop PV systems. PV technology is well suited for rooftop applications because of its modularity, the use of available space where the sun shines, and the benefits of generating electricity for building loads on site. There are practical and safety related considerations for installing electric generators on a roof, and one that has become more and more apparent to the PV industry is the impact to firefighters and their operations. As with other rooftop mounted equipment, PV panels present physical obstacles, and they can cover significant portions of a roof. Moreover, because it is powered by the sun, PV doesn't de-energize simply by shutting off the utility supply. Changes to building and electrical codes in the past few years have addressed some of the challenges with respect to firefighter access and electrical safety, but there is more work to do to further reduce potential hazards. DNV GL's position is that the safety of firefighters and other personnel involved with rooftop systems is of primary importance.

This paper summarizes findings from a DNV GL study of firefighter rooftop operations, the hazards that they may encounter when working around PV arrays, and means in which electrical hazards in particular can be mitigated or substantially reduced. It is hoped that the information and results can be useful in the ongoing development of new codes and standards related to PV systems and firefighter safety.

In addition to a review of relevant literature, there are two major components to the study: First, in-depth interviews with firefighters were conducted to better understand the rooftop operations, their concerns, and their decision making processes. The results of these interviews, along with information in the literature, help to define a set of requirements for developing technical solutions. Next, an engineering evaluation of electrical hazards and mitigation approaches was conducted using a Failure Mode and Effects Analysis (FMEA) based methodology.

3 BACKGROUND

There are a number of reasons for firefighters to get on the roof of burning buildings, the most prevalent of which is a tactic called vertical ventilation. In a residence for example, firefighters will cut a hole in the roof above the "seat" (or hottest part) of the fire to allow trapped smoke and hot gasses to rise out of the building. This enables the firefighters to advance inside the building to the seat to fight the fire and/or perform rescue operations. It can also mitigate backdraft conditions where a large and dangerous pressure differential exists between rooms. Vertical ventilation is useful when the smoke and gasses are trapped below the roof, such as in the rooms or walls of a single story structure, or the upper floor or attic of a multi-floor structure. Vertical ventilation is not required for all situations, and there are trends within the firefighter industry itself to move away from its use as a tactic in favor of more strategic horizontal ventilation options. However, there are times when vertical ventilation is still a critical option for effective firefighting and rescue operations.

On residences, firefighters will also get on the roof to tackle chimney fires, rooftop object fires, or rescue operations. On commercial buildings there are a number of tactics that involve putting personnel on the roof:

- Vertical ventilation, similar to residences. Vertical ventilation in commercial buildings can also be achieved using existing openings, such as skylights and vents.
- Trenching – a "trenched" line or long ventilation hole that is used as a firebreak of sorts, to prevent fire from spreading into other parts of the building or to adjacent buildings.

- Probing (or “sounding”) – a tactic used to determine the progress of the fire and damage in a building. One method is to pound the roof with the blunt side of an axe to determine softness.
- Tackling rooftop HVAC unit fires or failures – these units may either catch fire or be the source of smoke, gas or other smells in the building.
- Investigating a smoke source – e.g. when smoke is pumping into the building from the roof.

2015 IFC Requirements

Residential Roof

- *3’ ridgeline setback for 2’ wide ventilation cut*
- *3’ pathways on array faces, (2) for single ridge*
- *3’ at or spanning hip (1.5’ either side)*

Commercial Roof

- *4’–6’ perimeter space, function of bldg. size*
- *Min. 4’ center access and to skylights, standpipes and hatches.*
- *150’ max dimension without pathway*

2014 NEC 690.12 Requirements

- *Rapid shutdown controls specific conductors*
- *Controlled conductors are 10’ from array, 5’ inside building from entry*
- *Limited to 30V/240VA within 10 seconds of initiation*

2017 1st Draft NEC Requirements

- *Control limits for outside and inside array:*
  - *Outside: 1’ from array boundary in any direction; 30V, 10 seconds*
  - *Inside: 80V, 10 seconds*
- *Three initiation methods defined.*

3.1 Impact of PV on Firefighter Operations

How does rooftop PV impact these firefighter operations? It matters whether or not the PV array itself is on fire, but where the array is not involved in the fire, the single most significant impact is access. The 2012 and particularly the 2015 International Fire Code (IFC) included revisions requiring setbacks and pathways where previously none were uniformly required (see sidebar). Without these requirements, rooftops could be completely carpeted with PV, making it virtually impossible for firefighters to get on the roof. This was a critical factor for firefighters on the scene of the 2013 Dietz and Watson warehouse fire in New Jersey. With the access requirements, firefighters can get on and around the roof, even if the possible locations for vertical ventilation are limited. This is the more typical outcome of fires to date. Other impacts include the following:

- Trip or slip hazards, particularly if visibility on the roof is poor and firefighters need to make quick egress.
- Roof structure integrity due to the additional weight of the PV array on the roof.
- The risk of inadvertent electrical shock, should a firefighter come in contact with damaged array components, or cause damage to the components.
- The level of perceived electrical hazard risk by individual firefighting units and incident commanders.

Each of these impact the decision making process for rooftop operations, and are discussed in more detail in the survey and risk-mitigation analysis sections of this paper.

When the PV array itself is involved in a fire, the impacts extend to the techniques employed to extinguish the fire with potentially energized circuits. Two comprehensive studies conducted in the U.S. and in Germany have come to similar conclusions and prescriptions for safely fighting fires in PV arrays. With the proper techniques firefighter operations are safe with existing PV and array technology (see UL testing sidebar) [1]. Despite these similarities, the policy direction of code requirements in the two countries differs significantly. In Germany, which has the largest number of rooftop PV installations of any country, a joint industry study (involving the Fraunhofer Institute for Solar Energy, TUV Rheinland, and a Munich Fire Brigade, among others) developed guidelines for operations that emphasize the establishment of safe boundaries and firefighting tactics [2]. Their report notes the limited ability to reliably de-energize circuits within a PV array, particularly under the damaging conditions associated with a building fire. Moreover, the report noted that there are not sufficiently established module level disconnection technologies or standards to warrant a technology mandate. While products are available, some showing great promise in the relatively short term of their existence in the field, the technology is considered still to be unproven relative to the established long term reliability of PV modules themselves. The main concern with such a mandate is long-term reliability, both for the PV system operation as a whole, and for the safety devices that would be relied upon by firefighters for a 20 year or greater design life. The latter is feared to create a false sense of security regarding the safety of potentially damaged array equipment, and therefore would not result in any changes to the tactical procedures of working around an array.

The direction currently being taken in the U.S. is very different. Revisions in the current draft of the 2017 NEC article 690.12 (Rapid Shutdown of PV Arrays) require disconnection at the module level for all rooftop systems by establishing a limit of 80V between any two conductors and between any conductor and ground. The 80V limit was intended to cover the maximum voltage of the majority of module products currently on the market, although there are many models that do exceed 80V. This requirement is highly contentious in the PV industry for the reasons noted in the summary of the German report above, among others. The fact is, the NEC will be mandating the use of products (electronic devices operating in punishing conditions) that have far less field experience than the established technologies that will be sidelined in the market should the draft requirements be officially adopted. Commercial interests are unquestionably significant on both sides of this issue, but the concerns over reliability are voiced equally by experts at research institutes, universities, and National Laboratories operated by the U.S. Department of Energy.

UL Firefighter Safety and PV – Findings

- *Shock hazard from hose stream eliminated with distances of 15' from 600V sources and 20' from 1,000V sources, or if a 10° cone angle is used.*
- *Thresholds of current defined for different levels of shock hazard – assumes (worst case) 500Ω body impedance*
- *>40 mA above unsafe*
- *2-40 mA startle hazard*
- *Tarp coverings not recommended - generally must be dark and heavily woven to be effective, and can be unsafe.*
- *PV capable of producing unsafe currents when illuminated by truck lights or fire.*
- *Current magnitude and durations provided for conductor cutting and module damage.*
- *Dangerous conditions from damaged arrays identified.*

It is with this context that the firefighter surveys and risk-mitigation analysis conducted as part of this study were developed: What are the firefighter operations that put them at risk of electrical shock? What are the real-world electrical shock scenarios and mechanisms created by these operations? (No real data exists on this last question because to date there is no reported incident of firefighter injury by a PV system.) How do the risks, both real and perceived, impact tactical decisions? How would requirements for enhanced protection in the array impact those tactical decisions? What level of indication is necessary for firefighters to trust that a safety function has operated as expected? What is the expectation or requirement of equipment that has been damaged by the fire or firefighting operations? What objective requirements for solutions can be developed from the findings? Are there other means of mitigating the risk of shock, with similar outcomes in effectiveness and tactical decision-making, which do not mandate specific product solutions?

4 FIREFIGHTER SURVEYS

4.1 Background and Content

DNV GL conducted formal survey-based interviews with eleven firefighters and had additional brief conversations with other firefighting industry representatives. Altogether these interviews added up to well over 10 hours of discussions. The firefighters included several incident commanders and high level battalion officers, representatives from the International Association of Fire Chiefs and the International Association of Fire Marshalls, members of the International Association of Fire Fighters, and a lead fire protection engineer. The firefighters surveyed serve in departments of all sizes, from small towns to large cities and geographically spread throughout the U.S. Most of the interviewees serve in areas where PV systems are common, even if they did not have direct experience fighting fires on buildings with PV. Two were incident commanders at high profile commercial building fires involving PV (the Dietz and Watson fire in New Jersey and the Apple facility fire in Mesa, Arizona). One interviewee is the successor to the incident commander in the department that fought a PV fire on a large commercial rooftop in Redlands, California, and was well informed about the incident. Several of the interviewees had had training on PV and firefighter operations, and one is a trainer on the topic. The remainder had little or no formal PV training.

Without exception the firefighters interviewed were helpful, generous with their time and attention to detail, patient (when explaining new concepts), and frank in their opinions. DNV GL and the project sponsors are grateful for their time and contributions.

The interview content was structured around questions addressing the procedures, issues, and decisions that firefighters face when carrying out operations at a building that has rooftop PV. These included the initial steps of identifying the PV system’s presence, disconnecting procedures, working around the arrays, fighting fires with or without the involvement of the array, and post-fire overhaul protocols. Conversations focused on the impact of changing IFC and NEC requirements, how the presence of PV arrays impacts operational decision-making, and opinions related to additional controls to reduce shock hazards within the array.

4.2 Major Findings

Respondents reported that the improved setbacks and pathways instituted in the 2015 IFC are a great help in many aspects, particularly with enabling firefighters to get on the roof to investigate, create paths for hose lines, and ensure one or more egress paths. This enables operations that would otherwise not be considered at all. However, in some cases the desired ventilation point could still be under the array, and ventilating in a different location can cause more harm than good by creating a path for the fire to spread. The 3’ ridgeline access requirements may be useful given the objective to ventilate as high as possible, but some respondents suggested that cutting so close to the ridgeline might compromise structural stability and would be avoided. Ventilation on commercial buildings is impacted less by PV arrays if skylights and vents are accessible and capable of providing a ventilation path without cutting holes in the roof. The location for trenches to set fire breaks can likely use existing array pathways, but some respondents indicated that specific building features determine the best trench locations, and array pathways should be planned accordingly. These issues deserve additional attention by the fire service and PV community to provide continual improvements.

Figures 1 and 2 illustrate key findings from questions posed to the respondents at the end of the interviews. Figure 1 summarizes the responses when firefighters were asked their three top concerns related to rooftop PV systems and firefighting operations. In the context of the discussion these are indicative of the ultimate or long-term needs of the fire service. Figure 2 summarizes the firefighters' response when asked what they would like to see in the near-term from the PV industry given the current level of maturity of products.

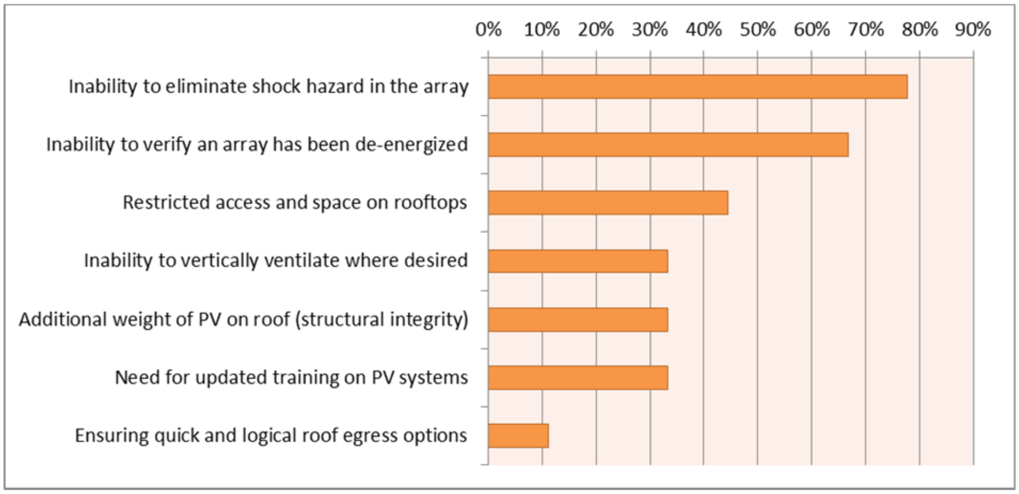

Figure 1: Main concerns reflecting long term needs and objectives

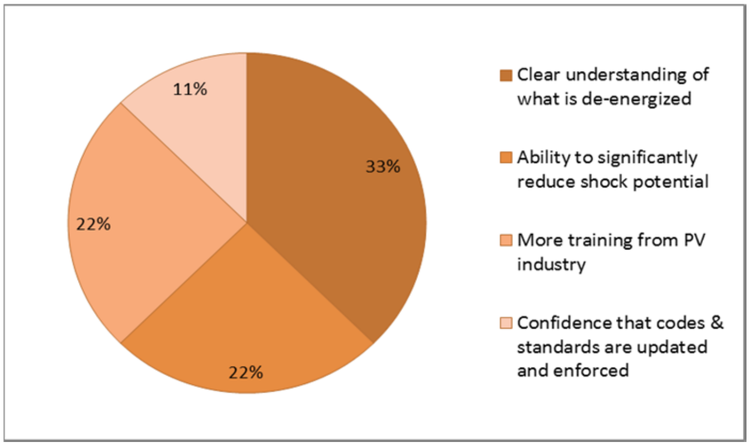

Figure 2: Summary of near term needs (from the PV industry)

The ability to reduce or eliminate shock hazard plays prominently in both responses, and was the most cited long term objective. A clear understanding of what is de-energized (and what isn't) was emphasized as well, and was most cited for short-term needs. This shift is due partly to the firefighters' awareness that codes and requirements are evolving and that the protection in place at systems they encounter can vary significantly.

Shock hazard reduction and verification together are viewed by all respondents as the only real way to address concerns related to accidental contact (by fall or trip) or the need to get across the array in an emergency (for example if an egress path were to suddenly be blocked by events in the operation). Respondents expressed the desire for rapid shutdown functions to work under damaged conditions, but none expected that they would. All would treat damaged arrays as energized. (All were made aware that the standard being developed for the evaluation of rapid shutdown components will not address fire or heat damage.) Some respondents expressed the desire for comprehensive positive indication that the rapid-shutdown function operated as intended. For internal array controls, an example was light indicators in the array or some similar visual method. Most however were accepting of some higher level indication that did not provide complete assurance.

Two of the respondents reported that they would consider intentional interaction, such as removing modules to ventilate underneath, if they had knowledge that the array was de-energized. However, most said they would not due to the understanding that damaged modules still could present some electrical hazard, and the time required to ventilate under an array is likely too long to be effective. Those in leadership roles said they would not direct firefighters to remove modules because of these risks.

Figure 1 also illustrates a number of concerns that are not electrical related. It is not in the scope of this study to address these issues specifically, but for the purpose of developing risk-based requirements it is important to understand where electrical shock considerations fit in the overall context of the decision making that takes place. These decisions are highly situation specific and are made quickly at the scene by incident commanders.

- Even without a PV array, the opportunity for rooftop operations (particularly vertical ventilation) is limited. Newer home construction employs lightweight trusses to support rooftops, which fail relatively quickly when exposed to the heat of a fire. Similarly, the speed at which the fire spreads is increased by the petrochemical based materials found in modern home furnishings and building materials (“solid state gasoline,” as one respondent called it). This greatly reduces the window of opportunity (relative to older home construction) to get on and off the roof before it becomes unstable for personnel.
- For buildings with arrays, the weight of the modules, as previously noted, potentially accelerates the loss of structural integrity as the fire progresses and shortens the window of opportunity for a successful roof operation.
- Trip or slip hazards are of concern, particularly if visibility is low or if there are other impediments to safe pathways.
- Misunderstandings of hazards from lack of adequate training have a clear impact on operations. A couple of respondents believed that arrays and modules were energized live exposed parts, even in undamaged conditions, and would not send personnel to the roof if an array was present. Several were unaware of the ability to safely extinguish an array fire with water hoses given the appropriate distances, cone angles or use of broken spray identified in the UL study.
- Operating decisions are also impacted by more or less accurate assessments of the electrical hazards. As one more factor in the list of risks that are evaluated quickly at the scene, the risk of accidental electric shock from a potentially compromised array may tip the scale to abort an operation, impacting the outcome to the building.
- Training, continual updates on technology and the knowledge that codes and standards are being enforced are critical to firefighter confidence in making sound tactical decisions. Training should emphasize case histories with successful outcomes, such as the Mesa and Redland commercial building fires. The incident commanders for these operations had knowledge and training in PV fire-fighting tactics, had adequate access paths on the roof and/or capabilities to engage the fire from ladders, and efficiently extinguished the arrays fires.

4.3 Requirements and Recommendations

What requirements and objectives can the PV industry take away from the survey and other information gathered? At a minimum, it is clear that complete and accurate knowledge of the hazards present is imperative for effective and sound decision making. The definition of working boundaries around the array established in the 2014 NEC and refined in the 2017 draft enables firefighters to perform their operations confidently around the identifiable equipment if conditions of access, visibility, and egress are also favorable.

If these conditions are not favorable, the decision to avoid a rooftop operation could be made regardless of whether array components are energized. By extension, the knowledge of the level or version of rapid shutdown compliance is important, as the requirements are changing with each code cycle. All of this points to the need for training and continual education on the evolving technology. It also points to the need for clear signage at the sites to identify the equipment and circuits that remain energized after rapid shutdown is initiated.

The ability to further de-energize circuits within undamaged arrays is seen as key to reducing the risk of accidental shock, but not as a rationale for intentional interaction. The real value of the enhanced electrical protection is its impact on the decision making; enabling firefighters to more confidently carry out operations and improve outcomes.

DNV GL recommends the following based on these findings:

- Requirements for clearly delineating controlled conductors and equipment outside the array boundary should be enhanced, along the lines of the approaches proposed by both PV and firefighter organizations for the 2017 code.
- Similarly, signage requirements should be enhanced to provide clear indication of which circuits are controlled, and which are not. Signage should not mislead by indicating that circuits with reduced shock hazard have no shock hazard.
- Enhanced electrical protection within the array boundaries should be pursued to reduce the risk of accidental shock and improve operational decision-making.
- Additional testing and fact based training should provide a clear understanding of the limited de-energization capabilities within the array, whether from 80V sources or from other means of reducing shock potential.
- Firefighters should be trained that they should not intentionally interact with the array under virtually any circumstance due to these limited de-energization capabilities and the inability to know if rapid-shutdown functionality has been compromised by any number of causes. They should also be trained to understand that in normal conditions arrays do not pose a safety hazard unless something damages them.
- There is no technical or operational rationale for mandating a specific solution for reducing the electrical hazards internal to the array.
- Standards and code committees should employ quantitative analyses to define criteria for reducing the electrical hazards and allow the industry to develop a range of solutions to meet those criteria. Additional testing to supplement the 2011 UL fire-safety testing will be needed to better quantify the effectiveness of different solutions.

5 RISK-MITIGATION ANALYSIS

DNV GL conducted a risk-mitigation analysis that evaluates specific electrical shock scenarios and methods for reducing the shock potential inside the boundaries of an array. The analysis follows the basic structure of an FMEA, which incorporates three variables to create a score for comparative purposes:

- *Severity*: The degree of the hazard or severity of impact for each shock scenario.
- *Occurrence*: The probability of the shock scenario on a relative basis.

- *Detection*: The relative capability or effectiveness of the solutions to mitigate the hazard.

The end result is a quantitative comparison and prioritization of corrective actions that incorporates mitigation effectiveness but also gives greater weight to approaches that address the higher probability scenarios.

5.1 Analysis development process

The process for developing risk scenarios and mitigation options specific to the firefighter operations involved three steps:

1. A listing of the operational and tactical risks that firefighters encounter at a residence or commercial building. From this larger list, a short list of risks that would be directly (and positively) impacted by reduced electrical shock hazard internal to the array was created.
2. The short list of operational risks identified in step 1 was then used to create a list of corresponding electrical shock scenarios that could occur (involving the person performing these operations.)
3. A detailed look at the electrical shock scenarios developed in (2) and how a range of rapid shutdown mitigation approaches impact their hazard potential.

Figure 3 summarizes the flow and key components of the analysis for the residential building case. Detailed tables are shown in Appendix A. The operations column summarizes 49 operational risks that were identified for residential rooftop operations covering electrical and non-electrical issues (Appendix Fig. A-1). Only eleven of those were identified as being impacted by enhanced electrical protection internal to the array. Three of the eleven involved intentional disruption of the array and are treated as extremely low probability in the FMEA. The relevant hazards from these operations mostly involve inadvertent damaging contact with array components, or inadvertent contact with already damaged components. The term "damaged" is used broadly to include damaged conductors, broken modules, exposed live parts, etc.

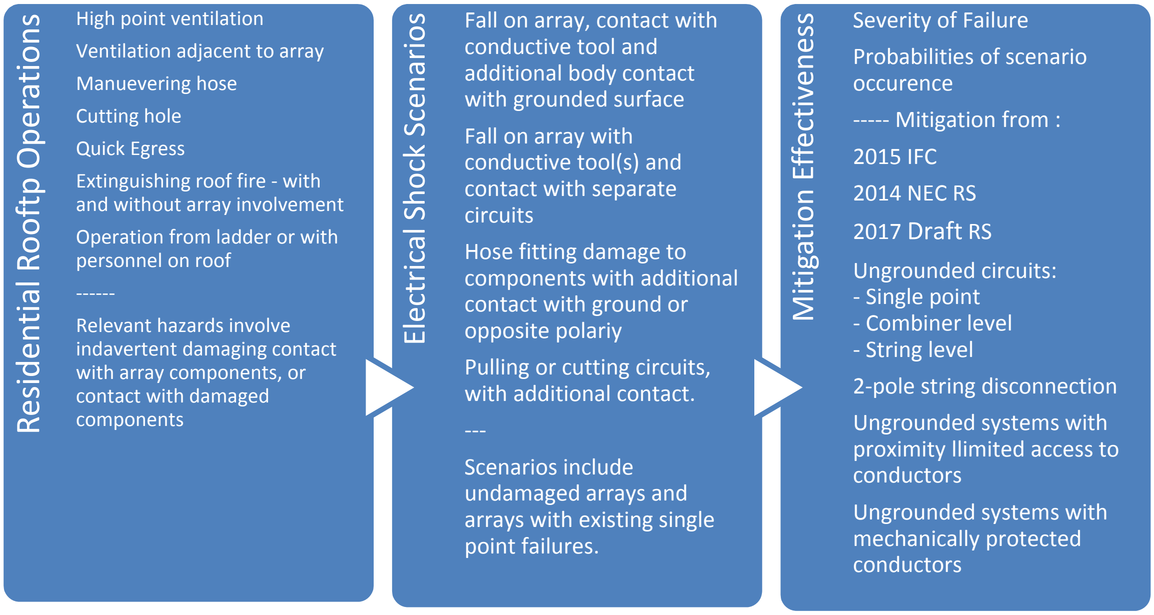

Figure 3: Flow and Components of Risk-Mitigation Analysis

Hazards do not exist under normal conditions in which 1) there are no damaged components or exposed live parts, and 2) firefighter contact does not cause damage. For the commercial building case there were 69 distinct operational risks identified (Appendix Fig. A-2). Twelve were identified as being impacted by enhanced electrical protection internal to the array, and two of the twelve involved intentional disruption of the array components.

The second column summarizes a list of actual shock scenarios -- in which a firefighter simultaneously makes physical contact with unimpeded parts at two different voltage potentials. One relatively plausible example is a scenario in which a person falls onto an undamaged array and punctures a module or live circuit (relative to ground) with a conductive tool, has skin contact with that conductive tool, and simultaneously has a separate low impedance contact with a grounded surface, e.g. through a damaged boot or glove. Ground contact could also be via standing water or a metal roof. For an array with existing damage, the initial contact with a part does not have to induce damage. Other scenarios are less probable, such as making damaging contact simultaneously with opposite circuits (not ground) with the body *between* those circuits, or hose fitting in contact with a live part and with a person in the conductive path. Details of the residential and commercial lists are shown in Appendix Fig. A-3 and A-4.

The third column summarizes mitigation options that can reduce the electrical shock risk and/or severity for the identified shock scenarios. These options include the 2015 IFC requirements, the 2014 NEC 690.12 rapid shutdown requirements, tighter boundaries combined with 80V internal array limits (module level control) per the current NEC 2017 690.12 first draft, as well as a select number of methods that rely less on voltage criteria and more on limiting the ability of a person to create or be a part of a harmful electrical circuit. There is precedence in NEC Article 517.11 (Health Care Facilities) for identifying alternative methods of controlling electric shock hazard, paraphrased as follows: *Control of electric shock hazard may be achieved by methods such as limiting the electric current that might flow in an electrical circuit involving personnel with increased resistance of the conductive circuit, limiting access to exposed components that might become energized, reducing the potential difference between energized components, or by a combinations of such methods.*

The alternative mitigation options include combinations and variations of the following:

- Disconnecting the dc circuit from ground in one or multiple locations to prevent a person in contact with a live part from completing an electrical circuit.
- String level disconnection in one or both poles, in combination with disconnection from ground (also to prevent closed circuits)
- Wiring methods that limit proximity and simultaneous access of conductors of different polarities (or ground)
- Mechanically protected conductors to limit simultaneous access of different polarities (or ground).

Evaluations in this study include “normal” scenarios where there are no pre-existing faults (undamaged arrays) and scenarios involving an existing single point of failure (Appendix Figures A-5 and A-6). Multiple points of failure (e.g. from extensive heat or fire damage to the array) are not evaluated because none of the mitigation or protection approaches can be considered to reliably reduce shock hazard in such a case.

There can be numerous variations of these types of solutions, including additional active measures for ensuring that currents cannot flow if a person becomes part of a circuit in a failure state. These are not covered in detail here but it is hoped that this high level view will inspire further detailed analyses that can be supported by laboratory and field testing.

5.2 FMEA

When evaluating potential mitigation options, it is appropriate to give greater weight to solutions that are effective against the higher probability shock scenarios. For that reason, probabilities are assigned to the shock scenarios. Empirical data cannot be used since there are no known instances of firefighter injuries from interaction with PV systems. Therefore our analysis does not attempt to identify the actual odds, but rather assigns relative probabilities (FMEA Occurrence values) for comparative purposes. These relative probabilities are conservatively assigned as 5, 3, or 1 on a scale of 1-10 where 10 is the most likely. It is important to somehow reference the occurrence values to an identifiable real world condition nonetheless, and in this case the moderate case (5) is referenced to the occurrence of moderate to severe firefighter injuries attributed to electrical shock. According to NFPA firefighter injury studies covering the period of 2007 through 2011, an annual average of 40 moderate to severe firefighter injuries were attributed to electrical shock during fireground operations [10, 11]. This represents 0.12% of the total fireground injuries and a rate of approximately one electrical injury per 35,000 firefighting operations. If we make a very conservative assumption that in the future 1 out of the every 40 electrical shock injuries cited above is attributed to the more probable of the PV system shock scenarios, the rate associated with the FMEA occurrence value of 5 becomes 1/1,400,000. Stated another way, setting the target FMEA occurrence value to 5 or less assumes that fewer than one of every 34,000 fireground injures would be caused by a shock from a PV system.

The FMEA Severity value is tied to the severity of the impact for each scenario. As this FMEA is focused only on shock hazards, the impact is injury or death, and therefore the most severe value (10 on a scale of 1 to 10) is applied to all scenarios.

The FMEA Detection values are roughly categorized by their effectiveness in reducing the risk of electrical shock. Values assigned are 6 (Risk to personnel, based on current technology requirements, 4 (reduced risk), and 2 (low or significantly reduced risk). These are high level approximations that in future studies should be better quantified through actual testing. The scoring categories and values are summarized in Table 1.

Table 1: FMEA Scoring Criteria

Severity Score (1-10)		Occurrence Score (1-10)		Detection Score (1-10)	
10	All Cases	5	Moderate	6	Risk to personnel
		3	Low	4	Reduced risk
		1	Extremely Low	2	Low risk

Figures A-5 and A-6 in the Appendix show the risk-mitigation tables for residential and commercial operations, respectively. The key result for each mitigation option is its Risk Priority Number (RPN) score, which is the product of the Severity, Occurrence and Detection values. (The RPN has a built-in factor of 10 to incorporate the Severity score.) The lower the RPN value, the better the outcome. A summary of the average and maximum RPN scores for mitigation approach is shown in Tables 2 and 3, respectively. The risk categories in the first column of the tables each represent the collection of risks identified in Appendix Figures A-5 and A-6 for residential and commercial operations. The “normal” cases reflect undamaged arrays where there are no pre-existing faults and the shock hazard is caused by firefighter actions creating a fault. The single point failure cases reflect scenarios where a single pre-existing fault exists in the array or in the rapid-shutdown system.

Table 2: FMEA Results Summary: Average RPN Scores

Risk Category	2015 IFC	2014 Array RSS	80V MLC	Un-gnd Sys, single point	Un-gnd Sys, comb. box level	Un-gnd Sys, string level (1-pole)	String level disc. (2-pole)	Un-gnd Sys, conductors proximity and access limited	Un-gnd Sys, conductors mech. protected
Residential (Normal)	144	140	64	98	78	72	54	54	54
Residential (Single Point Failure)	153	149	76	138	116	80	62	71	71
Commercial (Normal)	132	108	60	90	74	68	50	50	50
Commercial (Single Point Failure)	140	136	71	107	82	76	58	67	67

Table 3: FMEA Results Summary: Maximum RPN Scores

Risk Category	2015 IFC	2014 Array RSS	80V MLC	Un-gnd Sys, single point	Un-gnd Sys, comb. box level	Un-gnd Sys, string level (1-pole)	String level disc. (2-pole)	Un-gnd Sys, conductors proximity and access limited	Un-gnd Sys, conductors mech. protected
Residential (Normal)	300	300	200	200	120	120	100	120	120
Residential (Single Point Failure)	300	300	200	300	200	180	120	180	180
Commercial (Normal)	300	300	200	200	120	120	100	120	120
Commercial (Single Point Failure)	300	300	200	200	180	180	120	180	180

The averaged results in Table 2 give an overall indication of how well the mitigation options address the full set of probability-weighted risks. The maximum RPN scores shown in Table 3 show the worst score for each mitigation option. These maximum values are typically used for comparative purposes when evaluating the different options. Values above 200 are of particular concern in this case because they exceed the product of moderate occurrence events (5), reduced risk (detection value 4), and severity (10). The values exceeding 200 are highlighted in orange in Table 3. Values of 200 or less are highlighted in green (and blue for lower values). By this criterion it is clear that the 2015 IFC and 2014 RSS requirements alone do not provide sufficient mitigation. Two-pole disconnection from ground at a single location such as in the inverter may be plausible for an undamaged array, but not an array with single point failure, and therefore is not an acceptable option. The scores of subsequent mitigation methods including the 80V module level control approach (as defined in the 2017 draft of 690.12 and labelled 80V MLC in the tables), combinations of 1 and 2 pole string level disconnection, access limited conductors, mechanical protected conductors, all meet the criteria.

With FMEAs such as this it is often less important to settle on a specific pass/fail threshold than it is to observe the relative difference or similarity in scores. Therefore an important conclusion from this FMEA is that solutions including the 80V requirement (module level control), multiple-point disconnection of circuits from each other and ground, and solutions that limit or protect access to circuits all scored similarly as effective measures to reduce the shock hazards within arrays.

It is also interesting to note that the average results table shows that mitigation methods result in lower overall risks for commercial systems than in residential systems. Occurrence values are adjusted downward along with some detection values due to the additional access, ease of movement, and less situational “need” to be in close proximity to runs of string wiring.

As stated earlier, this is a high-level analysis that needs expansion and refinement based on thorough analysis and testing of both the electrical shock scenarios and the effectiveness of different mitigation techniques (see additional considerations in the next section). No concrete conclusions can be made about the specific mitigation alternatives at this time; however it should be evident that there are multiple approaches for effectively achieving shock reduction objectives.

6 NEXT STEPS

DNV GL’s position is that the safety of firefighters and other personnel involved with rooftop systems is of primary importance. This paper demonstrates the need for additional work by the PV and firefighter industries to enhance training and knowledge, and to enhance the electrical safety of the arrays. There is currently no practical means of entirely eliminating shock hazard from PV arrays, particularly when the uncertainties of component failure in punishing environments and 20-25 year life expectations are considered. The surveys and risk-mitigation analyses point to expanded possibilities for reducing the electrical hazards, and the need for further investigation into various alternatives. Code requirements should be written preferably using a single set of requirements to allow alternatives and innovation within the industry to achieve these goals.

DNV GL recommends supplemental testing to the UL Firefighter tests that were conducted in 2011. Specifically, test procedures should be developed that better capture the realistic scenarios for shock hazard identified in this study. For example, the existing tests used wires and conductive plates to close circuits that will not be present in actual conditions. The use of actual PV and roof systems will provide better context and result in more useful and practical guidelines for firefighter training and development of effective safety requirements. Evaluations should address differences between residential and commercial building operations, and those findings should also be incorporated in firefighter training.

Standards committees focused on rapid-shutdown technology need to expand on test procedures and criteria for evaluating the effectiveness of various mitigation methods. This includes developing a better understanding of transient currents available from ungrounded circuits at different array voltages and numbers of parallel connected sources of current. This will provide a greater quantitative basis for determining the shock potential of arrays without a closed circuit path, and guidance for the introduction of additional impedance, if necessary. Testing should also consider possible impacts of separated conductors so that secondary effects of such methods of preventing shock can be qualified.

Ongoing dialog between the PV and firefighting industries is paramount to the success of these objectives. DNV GL recommends continued and expanded involvement of stakeholders from both industries to ensure the best possible outcomes.

7 ACKNOWLEDGEMENTS

The study was commissioned through the Solar Energy Industry Association (SEIA) and sponsored by a group of PV industry leaders including, among others:

- NRG
- SMA America
- Solar City
- SunPower

DNV GL is grateful for the time and input provided by representatives of SEIA and the supporting companies. As mentioned in Section 3.1, DNV GL especially is grateful for the time and generosity provided by the firefighters interviewed for this study.

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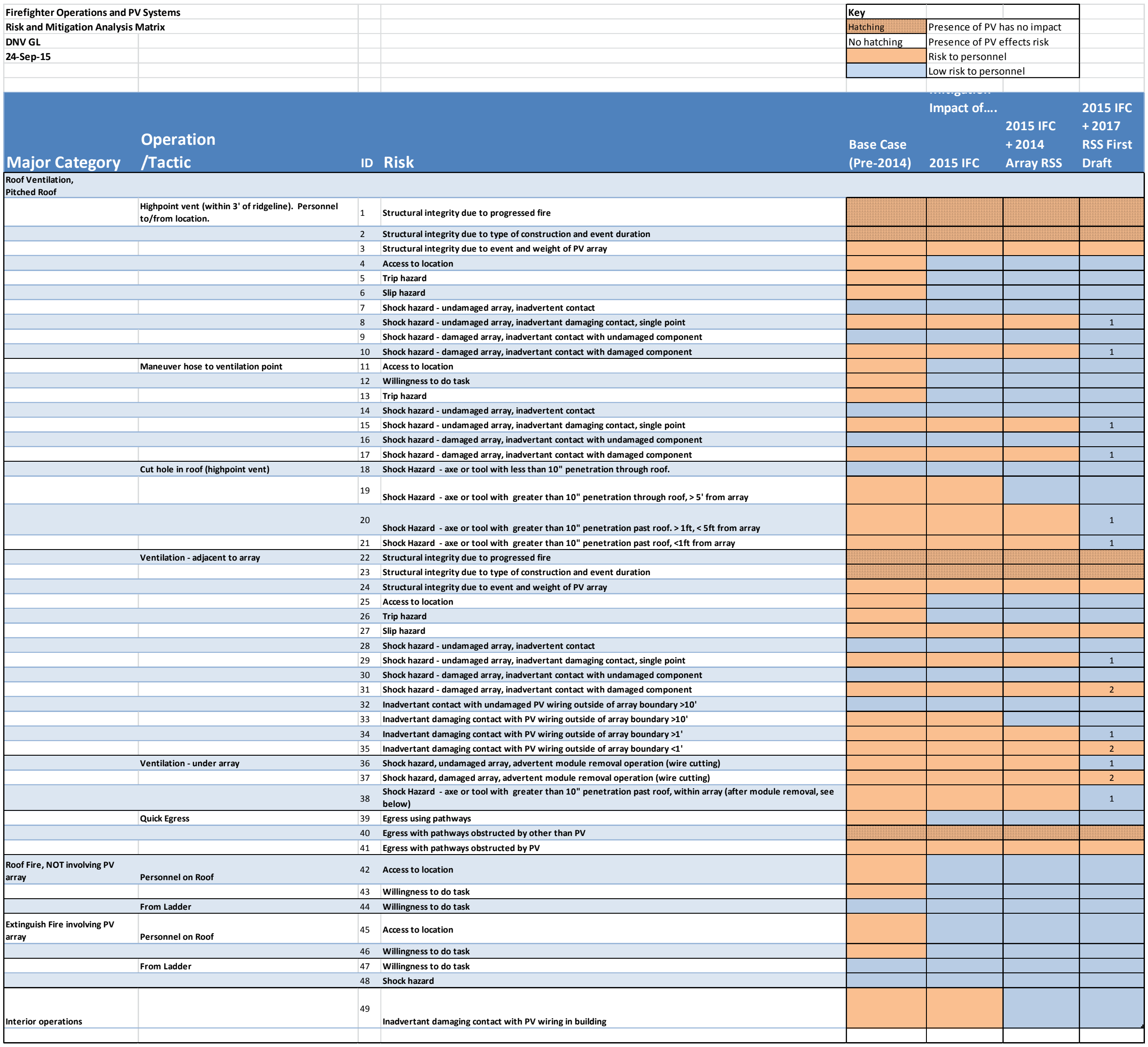
9 APPENDIX A – RISK/MITIGATION ANALYSIS CHARTS



Firefighter Operations and PV Systems
Risk and Mitigation Analysis Matrix
DNV GL
24-Sep-15

Key	
▨ Hatching	Presence of PV has no impact
No hatching	Presence of PV effects risk
🟧	Risk to personnel
🟦	Low risk to personnel

					Impact of....		
Major Category	Operation /Tactic	ID	Risk	Base Case (Pre-2014)	2015 IFC	2015 IFC + 2014 Array RSS	2015 IFC + 2017 RSS First Draft
Roof Ventilation, Pitched Roof							
	Highpoint vent (within 3' of ridgeline). Personnel to/from location.	1	Structural integrity due to progressed fire	▨	▨	▨	▨
		2	Structural integrity due to type of construction and event duration	▨	▨	▨	▨
		3	Structural integrity due to event and weight of PV array	🟧	🟧	🟧	🟧
		4	Access to location	🟧	🟦	🟦	🟦
		5	Trip hazard	🟧	🟦	🟦	🟦
		6	Slip hazard	🟧	🟦	🟦	🟦
		7	Shock hazard - undamaged array, inadvertent contact	🟦	🟦	🟦	🟦
		8	Shock hazard - undamaged array, inadvertant damaging contact, single point	🟧	🟧	🟧	🟦 1
		9	Shock hazard - damaged array, inadvertant contact with undamaged component	🟦	🟦	🟦	🟦
		10	Shock hazard - damaged array, inadvertant contact with damaged component	🟧	🟧	🟧	🟦 1
	Maneuver hose to ventilation point	11	Access to location	🟧	🟦	🟦	🟦
		12	Willingness to do task	🟧	🟦	🟦	🟦
		13	Trip hazard	🟧	🟦	🟦	🟦
		14	Shock hazard - undamaged array, inadvertent contact	🟦	🟦	🟦	🟦
		15	Shock hazard - undamaged array, inadvertant damaging contact, single point	🟧	🟧	🟧	🟦 1
		16	Shock hazard - damaged array, inadvertant contact with undamaged component	🟦	🟦	🟦	🟦
		17	Shock hazard - damaged array, inadvertant contact with damaged component	🟧	🟧	🟧	🟦 1
	Cut hole in roof (highpoint vent)	18	Shock Hazard - axe or tool with less than 10" penetration through roof.	🟦	🟦	🟦	🟦
		19	Shock Hazard - axe or tool with greater than 10" penetration through roof, > 5' from array	🟧	🟧	🟦	🟦
		20	Shock Hazard - axe or tool with greater than 10" penetration past roof. > 1ft, < 5ft from array	🟧	🟧	🟧	🟦 1
		21	Shock Hazard - axe or tool with greater than 10" penetration past roof, <1ft from array	🟧	🟧	🟧	🟦 1
	Ventilation - adjacent to array	22	Structural integrity due to progressed fire	▨	▨	▨	▨
		23	Structural integrity due to type of construction and event duration	▨	▨	▨	▨
		24	Structural integrity due to event and weight of PV array	🟧	🟧	🟧	🟧
		25	Access to location	🟧	🟦	🟦	🟦
		26	Trip hazard	🟧	🟦	🟦	🟦
		27	Slip hazard	🟧	🟧	🟧	🟧
		28	Shock hazard - undamaged array, inadvertent contact	🟦	🟦	🟦	🟦
		29	Shock hazard - undamaged array, inadvertant damaging contact, single point	🟧	🟧	🟧	🟦 1
		30	Shock hazard - damaged array, inadvertant contact with undamaged component	🟦	🟦	🟦	🟦
		31	Shock hazard - damaged array, inadvertant contact with damaged component	🟧	🟧	🟧	🟧 2
		32	Inadvertant contact with undamaged PV wiring outside of array boundary >10'	🟦	🟦	🟦	🟦
		33	Inadvertant damaging contact with PV wiring outside of array boundary >10'	🟧	🟧	🟦	🟦
		34	Inadvertant damaging contact with PV wiring outside of array boundary >1'	🟧	🟧	🟧	🟦 1
		35	Inadvertant damaging contact with PV wiring outside of array boundary <1'	🟧	🟧	🟧	🟧 2
	Ventilation - under array	36	Shock hazard, undamaged array, advertent module removal operation (wire cutting)	🟧	🟧	🟧	🟦 1
		37	Shock hazard, damaged array, advertent module removal operation (wire cutting)	🟧	🟧	🟧	🟧 2
		38	Shock Hazard - axe or tool with greater than 10" penetration past roof, within array (after module removal, see below)	🟧	🟧	🟧	🟦 1
	Quick Egress	39	Egress using pathways	🟧	🟦	🟦	🟦
		40	Egress with pathways obstructed by other than PV	▨	▨	▨	▨
		41	Egress with pathways obstructed by PV	🟧	🟧	🟧	🟧
Roof Fire, NOT involving PV array	Personnel on Roof	42	Access to location	🟧	🟦	🟦	🟦
		43	Willingness to do task	🟧	🟦	🟦	🟦
	From Ladder	44	Willingness to do task	🟦	🟦	🟦	🟦
Extinguish Fire involving PV array	Personnel on Roof	45	Access to location	🟧	🟦	🟦	🟦
		46	Willingness to do task	🟧	🟦	🟦	🟦
	From Ladder	47	Willingness to do task	🟦	🟦	🟦	🟦
		48	Shock hazard	🟦	🟦	🟦	🟦
Interior operations		49	Inadvertant damaging contact with PV wiring in building	🟧	🟧	🟦	🟦

Figure A-1: Firefighter Risk Summary by Operation/Tactic - Residential

The table rows list potential firefighter risks for a residential home fire, categorized by high level operation and the specific operation or tactic. The columns show the high level evaluation of "Risk" or "Low Risk" that exists with different implementations of IFC and NEC requirements. The base case assumes a system is built without IFC 2015 or 2014 NEC 690.12 requirements. Subsequent columns show the impact of additional requirements. Cells marked with a '1' identify risks that are impacted by the draft 2017 NEC RSS requirements. Cells marked with a "2" identify the operational risks that are not categorically reduced by any of the mitigation methods but have some degree of change that warrant additional analysis. Cells with hatching indicate that the operation and risk is not impacted by the presence of the PV system. These are included to provide the context that some of the major and most limiting factors firefighters face with respect to making decisions about rooftop operations have no dependence on the PV.

Firefighter Operations and PV Systems
Risk and Mitigation Analysis Matrix
DNV GL
24-Sep-15

Key	
▨ Hatching	Presence of PV has no impact
No hatching	Presence of PV effects risk
🟧	Risk to personnel
🟦	Low risk to personnel

Major Category	Operation /Tactic	ID	Risk	Base Case (Pre-2014)	Impact of.... 2015 IFC	2015 IFC + 2014 Array RSS	2015 IFC + 2017 RSS First Draft
Commercial Roof Ventilation							
	Skylight or pre-installed vent. Personnel to/from location.	1	Structural integrity due to progressed fire	▨	▨	▨	▨
		2	Structural integrity due to type of construction and event duration	▨	▨	▨	▨
		3	Structural integrity due to event and weight of PV array	🟧	🟧	🟧	🟧
		4	Access to location	🟧	🟦	🟦	🟦
		5	Trip hazard	🟧	🟦	🟦	🟦
		6	Slip hazard	🟧	🟦	🟦	🟦
	Ventilation - adjacent to array	7	Access to location	🟧	🟦	🟦	🟦
		8	Trip hazard	🟧	🟦	🟦	🟦
		9	Slip hazard	🟧	🟦	🟦	🟦
		10	Shock hazard - undamaged array, inadvertent contact	🟦	🟦	🟦	🟦
		11	Shock hazard - undamaged array, inadvertant damaging contact, single point	🟧	🟧	🟧	🟦 1
		12	Shock hazard - damaged array, inadvertant contact with undamaged component	🟦	🟦	🟦	🟦
		13	Shock hazard - damaged array, inadvertant contact with damaged component	🟧	🟧	🟧	🟧 2
		14	Inadvertant contact with undamaged PV wiring outside of array boundary >10'	🟦	🟦	🟦	🟦
		15	Inadvertant damaging contact with PV wiring outside of array boundary >10'	🟧	🟧	🟦	🟦
		16	Inadvertant damaging contact with PV wiring outside of array boundary >1'	🟧	🟧	🟧	🟦 1
		17	Inadvertant damaging contact with PV wiring outside of array boundary <1'	🟧	🟧	🟧	🟧 2
	Maneuver hose to ventilation point	18	Access to location	🟧	🟦	🟦	🟦
		19	Willingness to do task	🟧	🟦	🟦	🟦
		20	Trip hazard	🟧	🟦	🟦	🟦
		21	Shock hazard - undamaged array, inadvertent contact	🟦	🟦	🟦	🟦
		22	Shock hazard - undamaged array, inadvertant damaging contact, single point	🟧	🟧	🟧	🟦 1
		23	Shock hazard - damaged array, inadvertant contact with undamaged component	🟦	🟦	🟦	🟦
		24	Shock hazard - damaged array, inadvertant contact with damaged component	🟧	🟧	🟧	🟦 1
	Cut hole in roof (adjacent to array)	25	Shock Hazard - axe or tool penetrating roof at any length	🟦	🟦	🟦	🟦
	Ventilation - under array	26	Shock hazard, undamaged array, advertent module removal operation (wire cutting)	🟧	🟧	🟧	🟦 1
		27	Shock hazard, damaged array, advertent module removal operation (wire cutting)	🟧	🟧	🟧	🟧 2
		28	Shock Hazard - axe or tool penetrating roof at any length, within array (after module removal)	🟦	🟦	🟦	🟦
	Quick Egress	29	Egress using pathways	🟧	🟦	🟦	🟦
		30	Egress with pathways obstructed by other than PV	▨	▨	▨	▨
		31	Egress with pathways obstructed by PV and other	🟧	🟧	🟧	🟧
Trenching	Trenching - adjacent to array	32	Structural integrity due to progressed fire	▨	▨	▨	▨
		33	Structural integrity due to type of construction and event duration	▨	▨	▨	▨
		34	Structural integrity due to event and weight of PV array	🟧	🟧	🟧	🟧
		35	Access to location	🟧	🟦	🟦	🟦
		36	Trip hazard	🟧	🟦	🟦	🟦
		37	Slip hazard	🟧	🟦	🟦	🟦
		38	Shock hazard - undamaged array, inadvertent contact	🟦	🟦	🟦	🟦
		39	Shock hazard - undamaged array, inadvertant damaging contact, single point	🟧	🟧	🟧	🟦 1
		40	Shock hazard - damaged array, inadvertant contact with undamaged component	🟦	🟦	🟦	🟦
		41	Shock hazard - damaged array, inadvertant contact with damaged component	🟧	🟧	🟧	🟧 2
		42	Inadvertant contact with undamaged PV wiring outside of array boundary >10'	🟦	🟦	🟦	🟦
		43	Inadvertant damaging contact with PV wiring outside of array boundary >10'	🟧	🟧	🟦	🟦
		44	Inadvertant damaging contact with PV wiring outside of array boundary >1'	🟧	🟧	🟧	🟦 1
		45	Inadvertant damaging contact with PV wiring outside of array boundary <1'	🟧	🟧	🟧	🟧 2
	Cut trench in roof membrane	46	Shock Hazard - axe or tool penetrating roof at any length	🟦	🟦	🟦	🟦
	Trenching - under or within array boundary	47	Willingness to do task	🟧	🟧	🟧	🟧
Commercial Roof Probing	Access to location	48	Access to location	🟧	🟦	🟦	🟦
		49	Trip hazard	🟧	🟦	🟦	🟦
		50	Slip hazard	🟧	🟦	🟦	🟦
	Probe actions	51	Shock Hazard - pound roof with blunt end of axe	🟦	🟦	🟦	🟦
		52	Willingness to do task	🟦	🟦	🟦	🟦
Investigate source of internal or external smoke	Personnel on Roof	53	Access to location	🟧	🟦	🟦	🟦
		54	Willingness to do task	🟧	🟦	🟦	🟦
Roof Fire, NOT involving PV array	Personnel on Roof	55	Access to location	🟧	🟦	🟦	🟦
		56	Willingness to do task	🟧	🟦	🟦	🟦
	From Ladder	57	Willingness to do task	🟦	🟦	🟦	🟦
Fire involving PV array	Personnel on Roof	58	Access to location	🟧	🟦	🟦	🟦
		59	Willingness to do task	🟧	🟦	🟦	🟦
		60	Shock hazard	🟦	🟦	🟦	🟦
	From Ladder	61	Willingness to do task	🟦	🟦	🟦	🟦
		62	Shock hazard	🟦	🟦	🟦	🟦
Interior operations		63	Inadvertant damaging contact with PV wiring in building	🟧	🟧	🟦	🟦

Figure A-2: Firefighter Risk Summary by Operation / Tactic - Commercial

Firefighter Operations and PV Systems
Risk and Mitigation Analysis Matrix
DNV GL
24-Sep-15

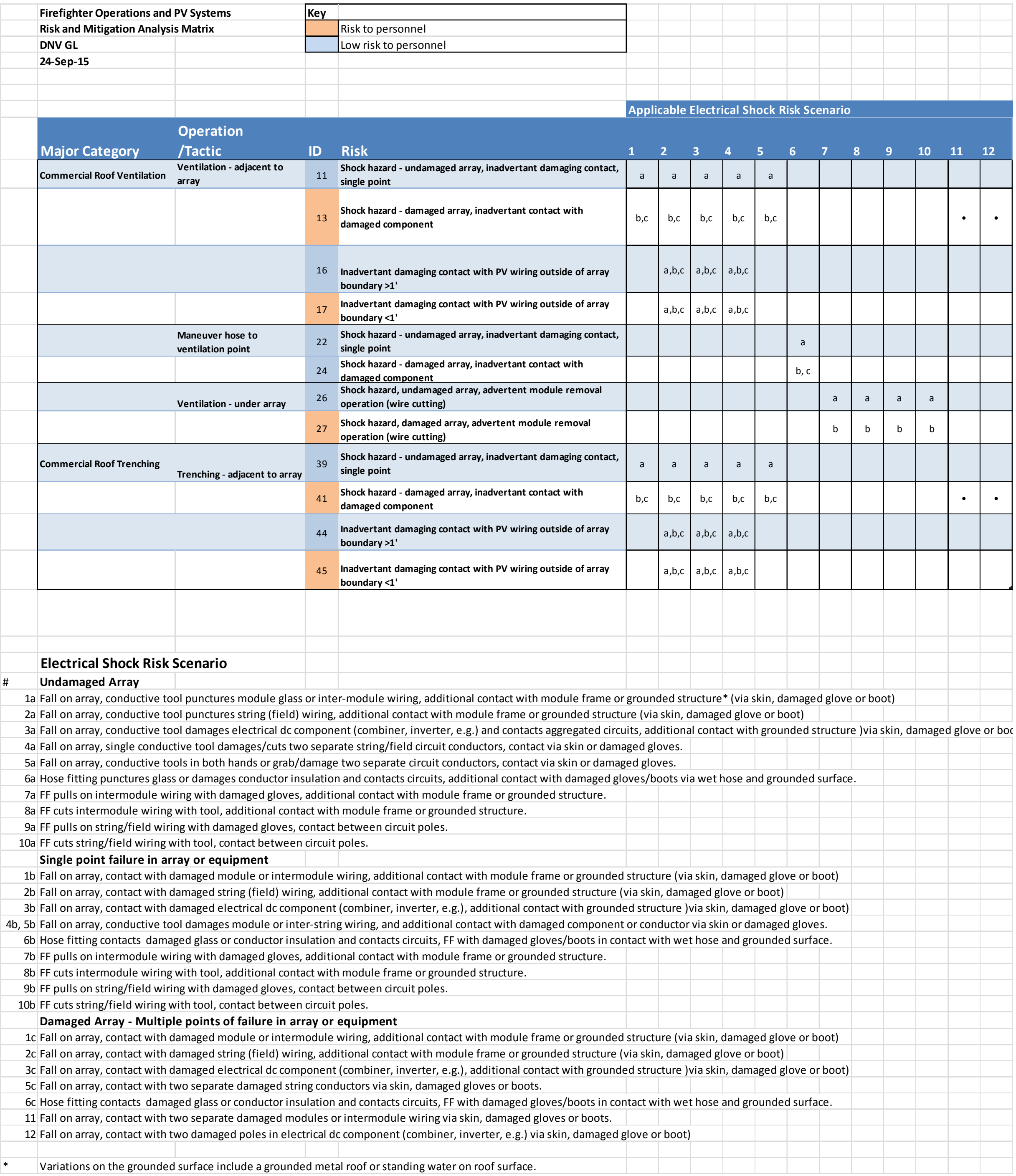
Key	
🟧	Risk to personnel
🟦	Low risk to personnel

				Applicable Electrical Shock Risk Scenario											
Major Category	**Operation /Tactic**	**ID**	**Risk**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Residential Roof Ventilation, Pitched Roof	Highpoint vent (within 3' of ridgeline). Personnel to/from location.	8	Shock hazard - undamaged array, inadvertant damaging contact, single point	a	a	a	a	a							
		10	Shock hazard - damaged array, inadvertant contact with damaged component	b,c	b,c	b,c	b,c	b,c						•	•
	Maneuver hose to ventilation point	15	Shock hazard - undamaged array, inadvertant damaging contact, single point						a						
		17	Shock hazard - damaged array, inadvertant contact with damaged component						b, c						
	Cut hole in roof (highpoint vent)	20	Shock Hazard - axe or tool with greater than 10" penetration past roof. > 1ft, < 5ft from array										a,b		
		21	Shock Hazard - axe or tool with greater than 10" penetration past roof, <1ft from array								a,b		a,b		
	Ventilation - adjacent to array	29	Shock hazard - undamaged array, inadvertant damaging contact, single point	a	a	a	a	a							
		31	Shock hazard - damaged array, inadvertant contact with damaged component	b,c	b,c	b,c	b,c	b,c						•	•
		34	Inadvertant damaging contact with PV wiring outside of array boundary >1'		a,b,c	a,b,c	a,b,c								
		35	Inadvertant damaging contact with PV wiring outside of array boundary <1'		a,b,c	a,b,c	a,b,c								
	Ventilation - under array	36	Shock hazard, undamaged array, advertent module removal operation (wire cutting)							a	a	a	a		
		37	Shock hazard, damaged array, advertent module removal operation (wire cutting)							b	b	b	b		
		38	Shock Hazard - axe or tool with greater than 10" penetration past roof, within array (after module removal, see below)								a,b		a,b		

#	Electrical Shock Risk Scenario
	Undamaged Array
1a	Fall on array, conductive tool punctures module glass or inter-module wiring, additional contact with module frame or grounded structure* (via skin, damaged glove or boot)
2a	Fall on array, conductive tool punctures string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
3a	Fall on array, conductive tool damages electrical dc component (combiner, inverter, e.g.) and contacts aggregated circuits, additional contact with grounded structure)via skin, damaged glove or boo
4a	Fall on array, single conductive tool damages/cuts two separate string/field circuit conductors, contact via skin or damaged gloves.
5a	Fall on array, conductive tools in both hands or grab/damage two separate circuit conductors, contact via skin or damaged gloves.
6a	Hose fitting punctures glass or damages conductor insulation and contacts circuits, additional contact with damaged gloves/boots via wet hose and grounded surface.
7a	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.
8a	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.
9a	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.
10a	FF cuts string/field wiring with tool, contact between circuit poles.
	Single point failure in array or equipment
1b	Fall on array, contact with damaged module or intermodule wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
2b	Fall on array, contact with damaged string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
3b	Fall on array, contact with damaged electrical dc component (combiner, inverter, e.g.), additional contact with grounded structure)via skin, damaged glove or boot)
4b, 5b	Fall on array, conductive tool damages module or inter-string wiring, and additional contact with damaged component or conductor via skin or damaged gloves.
6b	Hose fitting contacts damaged glass or conductor insulation and contacts circuits, FF with damaged gloves/boots in contact with wet hose and grounded surface.
7b	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.
8b	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.
9b	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.
10b	FF cuts string/field wiring with tool, contact between circuit poles.
	Damaged Array - Multiple points of failure in array or equipment
1c	Fall on array, contact with damaged module or intermodule wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
2c	Fall on array, contact with damaged string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
3c	Fall on array, contact with damaged electrical dc component (combiner, inverter, e.g.), additional contact with grounded structure)via skin, damaged glove or boot)
5c	Fall on array, contact with two separate damaged string conductors via skin, damaged gloves or boots.
6c	Hose fitting contacts damaged glass or conductor insulation and contacts circuits, FF with damaged gloves/boots in contact with wet hose and grounded surface.
11	Fall on array, contact with two separate damaged modules or intermodule wiring via skin, damaged gloves or boots.
12	Fall on array, contact with two damaged poles in electrical dc component (combiner, inverter, e.g.) via skin, damaged glove or boot)
*	Variations on the grounded surface include a grounded metal roof or standing water on roof surface.

Figure A-3: Shock Hazard Mapping of Firefighter Risks – Residential

The Figure A-3 table rows list the firefighter operational risks identified in Figure A-1 as having some risk reduction potential from 2017 NEC draft RSS requirements. The columns are the ID number for the applicable electrical shock scenarios that might occur as a result of the operational risk. Those shock scenarios are listed below in detail, and are categorized by scenarios with an undamaged array, an array with single point failure or damage, and an array with multiple failure points. Different scenarios that effectively have the same result or outcome have the same number, but are assigned a letter. For example, 1a, 1b, and 1c all result in the same shock potential to a person but are caused by different events. This approach groups the scenarios and reduces the number that need to be evaluated or tested.



Firefighter Operations and PV Systems
Risk and Mitigation Analysis Matrix
DNV GL
24-Sep-15

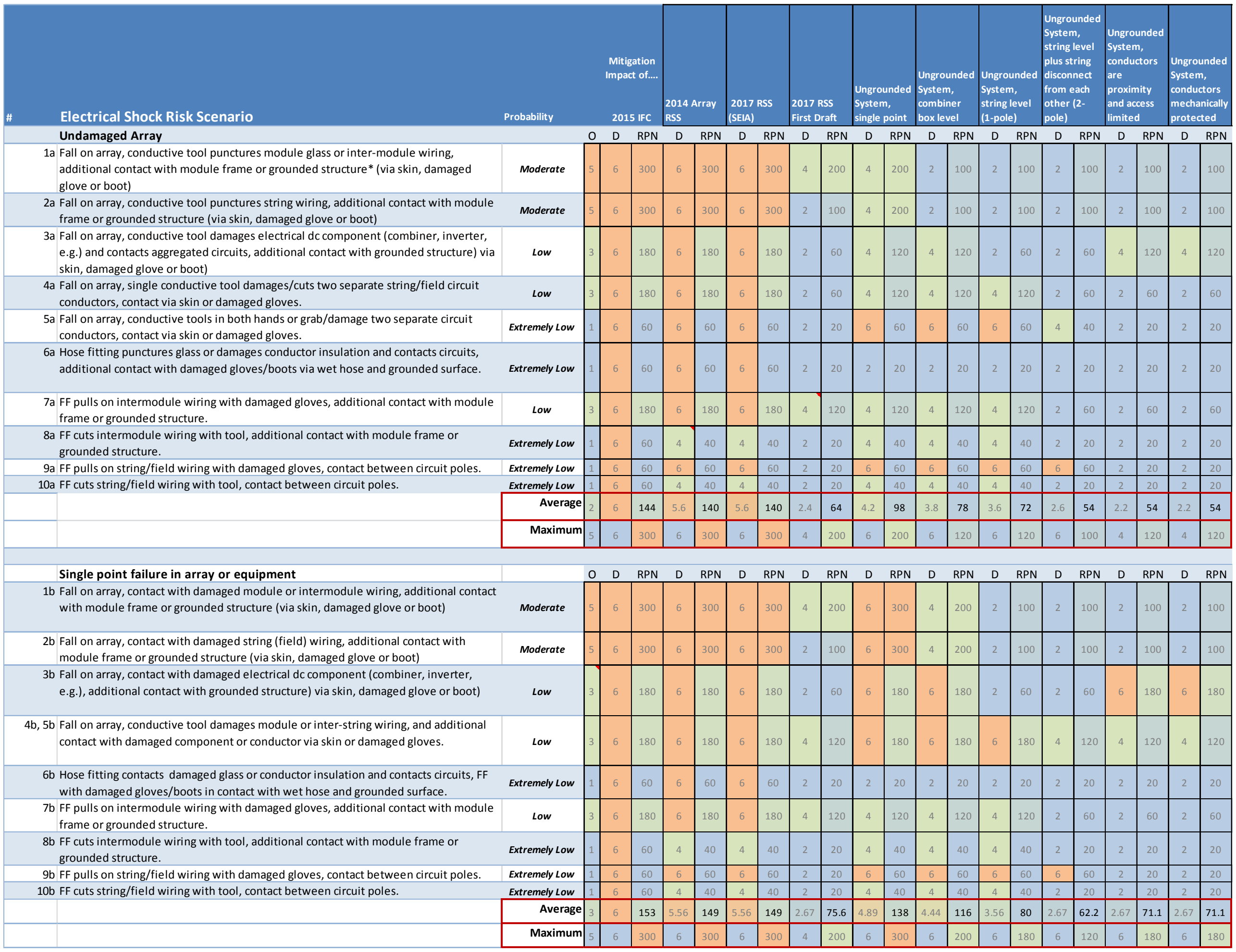
Key	
🟧	Risk to personnel
🟦	Low risk to personnel

				Applicable Electrical Shock Risk Scenario											
Major Category	**Operation /Tactic**	**ID**	**Risk**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Commercial Roof Ventilation	Ventilation - adjacent to array	11	Shock hazard - undamaged array, inadvertant damaging contact, single point	a	a	a	a	a							
		13	Shock hazard - damaged array, inadvertant contact with damaged component	b,c	b,c	b,c	b,c	b,c						•	•
		16	Inadvertant damaging contact with PV wiring outside of array boundary >1'		a,b,c	a,b,c	a,b,c								
		17	Inadvertant damaging contact with PV wiring outside of array boundary <1'		a,b,c	a,b,c	a,b,c								
	Maneuver hose to ventilation point	22	Shock hazard - undamaged array, inadvertant damaging contact, single point						a						
		24	Shock hazard - damaged array, inadvertant contact with damaged component						b, c						
	Ventilation - under array	26	Shock hazard, undamaged array, advertent module removal operation (wire cutting)							a	a	a	a		
		27	Shock hazard, damaged array, advertent module removal operation (wire cutting)							b	b	b	b		
Commercial Roof Trenching	Trenching - adjacent to array	39	Shock hazard - undamaged array, inadvertant damaging contact, single point	a	a	a	a	a							
		41	Shock hazard - damaged array, inadvertant contact with damaged component	b,c	b,c	b,c	b,c	b,c						•	•
		44	Inadvertant damaging contact with PV wiring outside of array boundary >1'		a,b,c	a,b,c	a,b,c								
		45	Inadvertant damaging contact with PV wiring outside of array boundary <1'		a,b,c	a,b,c	a,b,c								

Electrical Shock Risk Scenario

#	**Undamaged Array**
1a	Fall on array, conductive tool punctures module glass or inter-module wiring, additional contact with module frame or grounded structure* (via skin, damaged glove or boot)
2a	Fall on array, conductive tool punctures string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
3a	Fall on array, conductive tool damages electrical dc component (combiner, inverter, e.g.) and contacts aggregated circuits, additional contact with grounded structure)via skin, damaged glove or boc
4a	Fall on array, single conductive tool damages/cuts two separate string/field circuit conductors, contact via skin or damaged gloves.
5a	Fall on array, conductive tools in both hands or grab/damage two separate circuit conductors, contact via skin or damaged gloves.
6a	Hose fitting punctures glass or damages conductor insulation and contacts circuits, additional contact with damaged gloves/boots via wet hose and grounded surface.
7a	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.
8a	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.
9a	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.
10a	FF cuts string/field wiring with tool, contact between circuit poles.
	Single point failure in array or equipment
1b	Fall on array, contact with damaged module or intermodule wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
2b	Fall on array, contact with damaged string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
3b	Fall on array, contact with damaged electrical dc component (combiner, inverter, e.g.), additional contact with grounded structure)via skin, damaged glove or boot)
4b, 5b	Fall on array, conductive tool damages module or inter-string wiring, and additional contact with damaged component or conductor via skin or damaged gloves.
6b	Hose fitting contacts damaged glass or conductor insulation and contacts circuits, FF with damaged gloves/boots in contact with wet hose and grounded surface.
7b	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.
8b	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.
9b	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.
10b	FF cuts string/field wiring with tool, contact between circuit poles.
	Damaged Array - Multiple points of failure in array or equipment
1c	Fall on array, contact with damaged module or intermodule wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
2c	Fall on array, contact with damaged string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)
3c	Fall on array, contact with damaged electrical dc component (combiner, inverter, e.g.), additional contact with grounded structure)via skin, damaged glove or boot)
5c	Fall on array, contact with two separate damaged string conductors via skin, damaged gloves or boots.
6c	Hose fitting contacts damaged glass or conductor insulation and contacts circuits, FF with damaged gloves/boots in contact with wet hose and grounded surface.
11	Fall on array, contact with two separate damaged modules or intermodule wiring via skin, damaged gloves or boots.
12	Fall on array, contact with two damaged poles in electrical dc component (combiner, inverter, e.g.) via skin, damaged glove or boot)
*	Variations on the grounded surface include a grounded metal roof or standing water on roof surface.

Figure A-4: Shock Hazard Mapping of Firefighter Risks - Commercial



#	Electrical Shock Risk Scenario	Probability	Mitigation Impact of.... 2015 IFC			2014 Array RSS		2017 RSS (SEIA)		2017 RSS First Draft		Ungrounded System, single point		Ungrounded System, combiner box level		Ungrounded System, string level (1-pole)		Ungrounded System, string level plus string disconnect from each other (2-pole)		Ungrounded System, conductors are proximity and access limited		Ungrounded System, conductors mechanically protected	
	Undamaged Array		O	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN
1a	Fall on array, conductive tool punctures module glass or inter-module wiring, additional contact with module frame or grounded structure* (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	300	6	300	4	200	4	200	2	100	2	100	2	100	2	100	2	100
2a	Fall on array, conductive tool punctures string wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	300	6	300	2	100	4	200	2	100	2	100	2	100	2	100	2	100
3a	Fall on array, conductive tool damages electrical dc component (combiner, inverter, e.g.) and contacts aggregated circuits, additional contact with grounded structure) via skin, damaged glove or boot)	*Low*	3	6	180	6	180	6	180	2	60	4	120	4	120	2	60	2	60	4	120	4	120
4a	Fall on array, single conductive tool damages/cuts two separate string/field circuit conductors, contact via skin or damaged gloves.	*Low*	3	6	180	6	180	6	180	2	60	4	120	4	120	4	120	2	60	2	60	2	60
5a	Fall on array, conductive tools in both hands or grab/damage two separate circuit conductors, contact via skin or damaged gloves.	*Extremely Low*	1	6	60	6	60	6	60	2	20	6	60	6	60	6	60	4	40	2	20	2	20
6a	Hose fitting punctures glass or damages conductor insulation and contacts circuits, additional contact with damaged gloves/boots via wet hose and grounded surface.	*Extremely Low*	1	6	60	6	60	6	60	2	20	2	20	2	20	2	20	2	20	2	20	2	20
7a	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.	*Low*	3	6	180	6	180	6	180	4	120	4	120	4	120	4	120	2	60	2	60	2	60
8a	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
9a	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.	*Extremely Low*	1	6	60	6	60	6	60	2	20	6	60	6	60	6	60	6	60	2	20	2	20
10a	FF cuts string/field wiring with tool, contact between circuit poles.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
		Average	2	6	144	5.6	140	5.6	140	2.4	64	4.2	98	3.8	78	3.6	72	2.6	54	2.2	54	2.2	54
		Maximum	5	6	300	6	300	6	300	4	200	6	200	6	120	6	120	6	100	4	120	4	120
	Single point failure in array or equipment		O	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN
1b	Fall on array, contact with damaged module or intermodule wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	300	6	300	4	200	6	300	4	200	2	100	2	100	2	100	2	100
2b	Fall on array, contact with damaged string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	300	6	300	2	100	6	300	4	200	2	100	2	100	2	100	2	100
3b	Fall on array, contact with damaged electrical dc component (combiner, inverter, e.g.), additional contact with grounded structure) via skin, damaged glove or boot)	*Low*	3	6	180	6	180	6	180	2	60	6	180	6	180	2	60	2	60	6	180	6	180
4b, 5b	Fall on array, conductive tool damages module or inter-string wiring, and additional contact with damaged component or conductor via skin or damaged gloves.	*Low*	3	6	180	6	180	6	180	4	120	6	180	6	180	6	180	4	120	4	120	4	120
6b	Hose fitting contacts damaged glass or conductor insulation and contacts circuits, FF with damaged gloves/boots in contact with wet hose and grounded surface.	*Extremely Low*	1	6	60	6	60	6	60	2	20	2	20	2	20	2	20	2	20	2	20	2	20
7b	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.	*Low*	3	6	180	6	180	6	180	4	120	4	120	4	120	4	120	2	60	2	60	2	60
8b	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
9b	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.	*Extremely Low*	1	6	60	6	60	6	60	2	20	6	60	6	60	6	60	6	60	2	20	2	20
10b	FF cuts string/field wiring with tool, contact between circuit poles.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
		Average	3	6	153	5.56	149	5.56	149	2.67	75.6	4.89	138	4.44	116	3.56	80	2.67	62.2	2.67	71.1	2.67	71.1
		Maximum	5	6	300	6	300	6	300	4	200	6	300	6	200	6	180	6	120	6	180	6	180

Figure A-5: Residential Operation Risk-Mitigation Analysis Results

Figures A-5 and A-6 show the risk-mitigation tables for residential and commercial operations, respectively. The left hand columns list the detailed shock scenarios. The next columns “Probability” and “O” show the scenario probabilities and corresponding Occurrence scores. The remaining columns show the mitigation options with their Detection and final Risk Priority Number (RPN) score, which is the product of the Severity, Occurrence and Detection values. (The RPN has a built-in factor of 10 to incorporate the Severity score.) The lower the RPN value, the better the outcome.

#	Electrical Shock Risk Scenario	Probability	Mitigation Impact of.... 2015 IFC			2014 Array RSS		2017 RSS (SEIA)		2017 RSS First Draft		Ungrounded System, single point		Ungrounded System, combiner box level		Ungrounded System, string level (1-pole)		Ungrounded System, string level plus string disconnect from each other (2-pole)		Ungrounded System, conductors are proximity and access limited		Ungrounded System, conductors mechanically protected	
	Undamaged Array		O	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN
1a	Fall on array, conductive tool punctures module glass or inter-module wiring, additional contact with module frame or grounded structure* (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	300	6	300	4	200	4	200	2	100	2	100	2	100	2	100	2	100
2a	Fall on array, conductive tool punctures string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Low*	3	6	180	6	180	6	180	2	60	4	120	2	60	2	60	2	60	2	60	2	60
3a	Fall on array, conductive tool damages electrical dc component (combiner, inverter, e.g.) and contacts aggregated circuits, additional contact with grounded structure)via skin, damaged glove or boot)	*Low*	3	6	180	4	120	4	120	2	60	4	120	4	120	2	60	2	60	4	120	4	120
4a	Fall on array, single conductive tool damages/cuts two separate string/field circuit conductors, contact via skin or damaged gloves.	*Low*	3	6	180	4	120	4	120	2	60	4	120	4	120	4	120	2	60	2	60	2	60
5a	Fall on array, conductive tools in both hands or grab/damage two separate circuit conductors, contact via skin or damaged gloves.	*Extremely Low*	1	6	60	4	40	4	40	2	20	6	60	6	60	6	60	4	40	2	20	2	20
6a	Hose fitting punctures glass or damages conductor insulation and contacts circuits, additional contact with damaged gloves/boots via wet hose and grounded surface.	*Extremely Low*	1	6	60	6	60	6	60	2	20	2	20	2	20	2	20	2	20	2	20	2	20
7a	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.	*Low*	3	6	180	4	120	4	120	4	120	4	120	4	120	4	120	2	60	2	60	2	60
8a	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
9a	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.	*Extremely Low*	1	6	60	6	60	6	60	2	20	6	60	6	60	6	60	6	60	2	20	2	20
10a	FF cuts string/field wiring with tool, contact between circuit poles.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
		Average	2	6	132	4.8	108	4.8	108	2.4	60	4.2	90	3.8	74	3.6	68	2.6	50	2.2	50	2.2	50
		Maximum	5	6	300	6	300	6	300	4	200	6	200	6	120	6	120	6	100	4	120	4	120
	Single point failure in array or equipment		O	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN	D	RPN
1b	Fall on array, contact with damaged module or intermodule wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Moderate*	5	6	300	6	300	6	300	4	200	4	200	2	100	2	100	2	100	2	100	2	100
2b	Fall on array, contact with damaged string (field) wiring, additional contact with module frame or grounded structure (via skin, damaged glove or boot)	*Low*	3	6	180	6	180	6	180	2	60	4	120	2	60	2	60	2	60	2	60	2	60
3b	Fall on array, contact with damaged electrical dc component (combiner, inverter, e.g.), additional contact with grounded structure)via skin, damaged glove or boot)	*Low*	3	6	180	6	180	6	180	2	60	6	180	4	120	2	60	2	60	6	180	6	180
4b, 5b	Fall on array, conductive tool damages module or inter-string wiring, and additional contact with damaged component or conductor via skin or damaged gloves.	*Low*	3	6	180	6	180	6	180	4	120	6	180	6	180	6	180	4	120	4	120	4	120
6b	Hose fitting contacts damaged glass or conductor insulation and contacts circuits, FF with damaged gloves/boots in contact with wet hose and grounded surface.	*Extremely Low*	1	6	60	6	60	6	60	2	20	2	20	2	20	2	20	2	20	2	20	2	20
7b	FF pulls on intermodule wiring with damaged gloves, additional contact with module frame or grounded structure.	*Low*	3	6	180	6	180	6	180	4	120	4	120	4	120	4	120	2	60	2	60	2	60
8b	FF cuts intermodule wiring with tool, additional contact with module frame or grounded structure.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
9b	FF pulls on string/field wiring with damaged gloves, contact between circuit poles.	*Extremely Low*	1	6	60	6	60	6	60	2	20	6	60	6	60	6	60	6	60	2	20	2	20
10b	FF cuts string/field wiring with tool, contact between circuit poles.	*Extremely Low*	1	6	60	4	40	4	40	2	20	4	40	4	40	4	40	2	20	2	20	2	20
		Average	2	6	140	5.56	136	5.56	136	2.67	71.1	4.44	107	3.78	82.2	3.56	75.6	2.67	57.8	2.67	66.7	2.67	66.7
		Maximum	5	6	300	6	300	6	300	4	200	6	200	6	180	6	180	6	120	6	180	6	180

Figure A-6: Commercial Building Operation Risk-Mitigation Analysis Results

ABOUT DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.