UL 3741 Cost Comparison Whitepaper: DC-Optimized vs Non-DC-Optimized Solutions

Whitepaper

Background

With the recent adoption of the UL 3741 standard into the National Electric Code, a number of racking manufacturers have listed mechanical protection schemes as a replacement for traditional PV Rapid Shutdown equipment, most commonly in the form of Module-Level Power Electronics. These non-DC-optimized solutions have come with claims of decreased capital expenditures (CapEx) for C&I rooftop PV systems. However, there are substantial balance of system (BoS) cost increases that come with using such solutions, that should be considered when deciding on a solution for UL 3741 and NEC compliance.

This document details the analysis of 5 different rooftop systems, to compare the overall cost between SolarEdge DC-optimized solutions and other non-DC-optimized solutions.

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National Electric Code (NEC) History

Since its introduction in the 2014 NEC, rapid shutdown requirements have been evolving. The intent of this code section is to create a safe environment for firefighters responding to calls at buildings with rooftop PV arrays. Simple off switches for the electricity are not possible when it comes to solar power, so the need to control hazards was created.

Evolution of Rapid Shutdown Requirements

In the 2014 NEC, the requirements for rapid shutdown are as follows:

- Upon rapid shutdown initiation: Less than 30V within 10 seconds, outside the array boundary.
- The array boundary includes conductors within 10 ft of the array, or more than 5 ft inside a building. Intended to have the inverter installed within 10 ft of modules/racking.

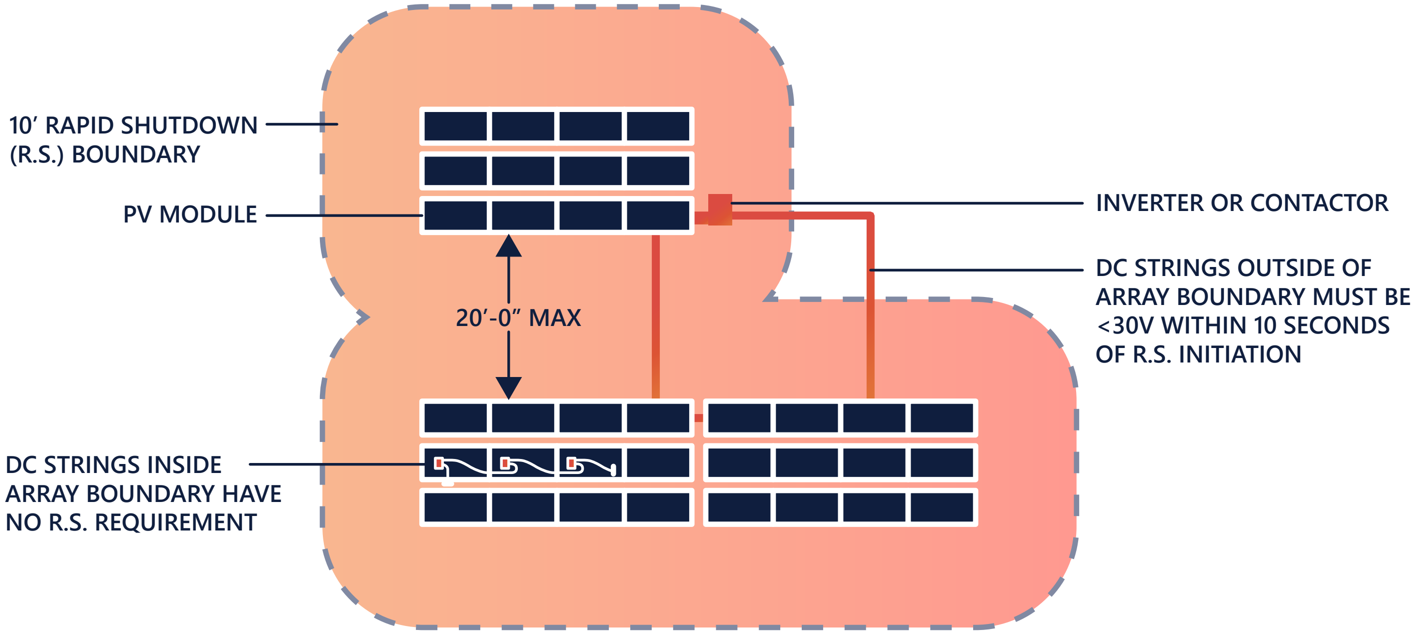


Figure 1: Rapid Shutdown Requirements – NEC 2014

In the 2017 NEC, the rapid shutdown requirements were updated such that the array boundary was defined as only 1-foot from the modules/racking:

- Upon rapid shutdown initiation: Less than 30V within 30 seconds, outside the array boundary.
- Inside the array:
  - Less than 80V within 30 seconds (using UL 1741 listed PV rapid shutdown equipment).
  - The PV array shall be listed, or field labeled as a rapid shutdown PV array.
  - Concealed wiring and no grounded metal within 8’ (BIPV).

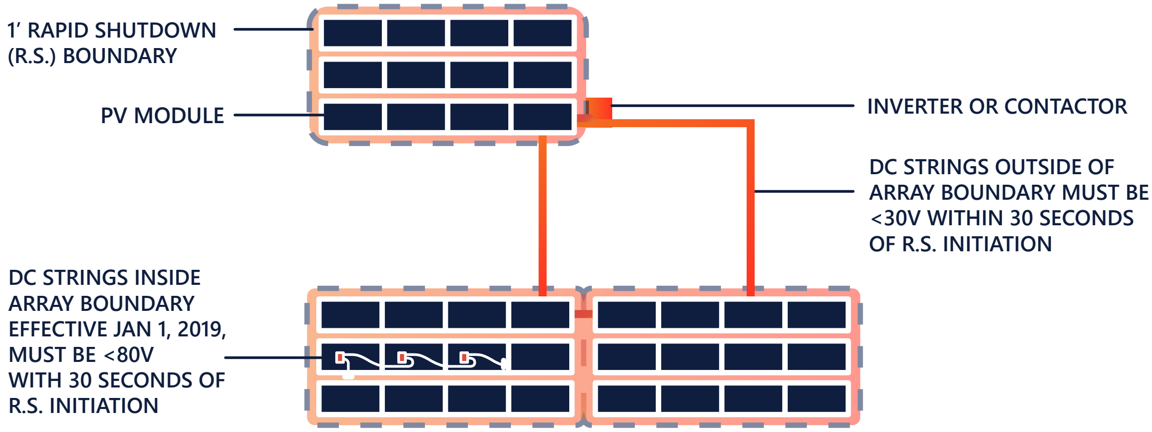


Figure 2: Rapid Shutdown Requirements – NEC 2017

The 2020 NEC defines the array boundaries in the same way as the 2017 NEC but offers different options for compliance regarding conductor control inside the array boundary.

- Upon rapid shutdown initiation: Less than 30V within 30 seconds, 1-foot outside the array boundary.
- Inside the array:
  - Less than 80V within 30 seconds (using UL 1741 listed PV rapid shutdown equipment).
  - A listed or field-labeled PV hazard control system system (PVHCS) as per UL 3741.
  - Concealed wiring and no grounded metal within 8' (BIPV).

An Intro to UL 3741

NEC 690.12 (B)(2) is the focal point of this standard, concerning the controlled conductors within a PV array boundary. UL 3741 was created as an option for meeting this requirement and was first introduced in the 2020 NEC. The standard is an effort to better define the risks for firefighters when working on or around PV systems. The previously defined threshold of 80V inside the array was a simple, conservative method to reduce hazards, 80V was already used for the arc-fault detection requirement.

The standard uses empirical methods to define the hazard level of voltages and currents within a PV array and a probabilistic assessment of exposure risk to those hazards for firefighters with OSHA-required safety gear and various fire-fighting tools. For example, if a firefighter falls on PV equipment with tools in their hands, what level of hazard are they exposed to?

To be listed as a PV Hazard Control System (PVHCS) under UL 3741 a piece of equipment or multiple coordinated pieces of equipment need to prove the function of reducing the risk of electric shock hazard within a damaged PV array for fire fighters.

Non-DC-Optimized Solution: Racking PVHCS at 1000VDC Max

Several racking manufacturers have listed UL 3741 compliant systems with string inverters that maintain string voltages up to 1000VDC. This energy source corresponds to corresponds to a hazard level 3 (under UL 3741), meaning the system must use additional measures to reduce the likelihood of exposure to these shock hazards for the firefighter, in full turnout gear. These systems, referred to here-on as "non-DC-optimized", use various combinations of non-metallic mechanical equipment and or separation from grounded metal to achieve the UL 3741 listing. 3 key components of the system are shared among every racking manufacturer's non-DC-optimized solution:

- Inverter's DC connection must be within the array boundary, meaning it is installed no more than 1-foot from the edge of the nearest module or racking structure. This ensures that all DC voltage is within the array boundary and can be controlled under the UL 3741 listing.

- Heavy emphasis is placed on wire management and covering any exposed cable within the array. Each racking manufacturer specifies the use of covered raceways, conduit (rigid or flexible), or other specifically listed equipment to cover the exposed cables. As well, methods and components for maintaining space between covered cables and module frames are specified by the racking manufacturer. The precise application of these wire management strategies is necessary for the system to remain UL 3741 compliant.

- The required use of listed PV rapid shutdown equipment (PVRSE) across the gap between array sections over 2-feet apart. The conductors that extend out of the array boundary, for example on a string or homerun that goes across multiple sub-arrays, must be controlled to <30V within 30 seconds to be code compliant. As such, additional equipment is required, the Figure 3 images below (from a racking manufacturer's installation manual) explains the options for doing so.

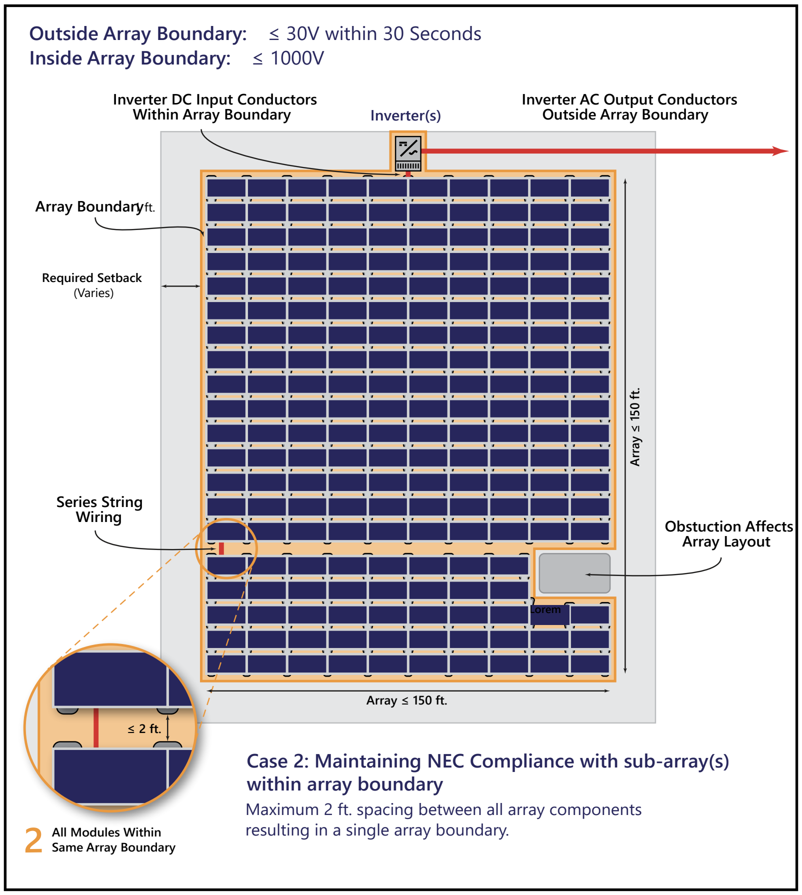


Figure 3: Racking Manufacturer Instructions for PVRSE on PV Sub-arrays
Image Source – Citation 8

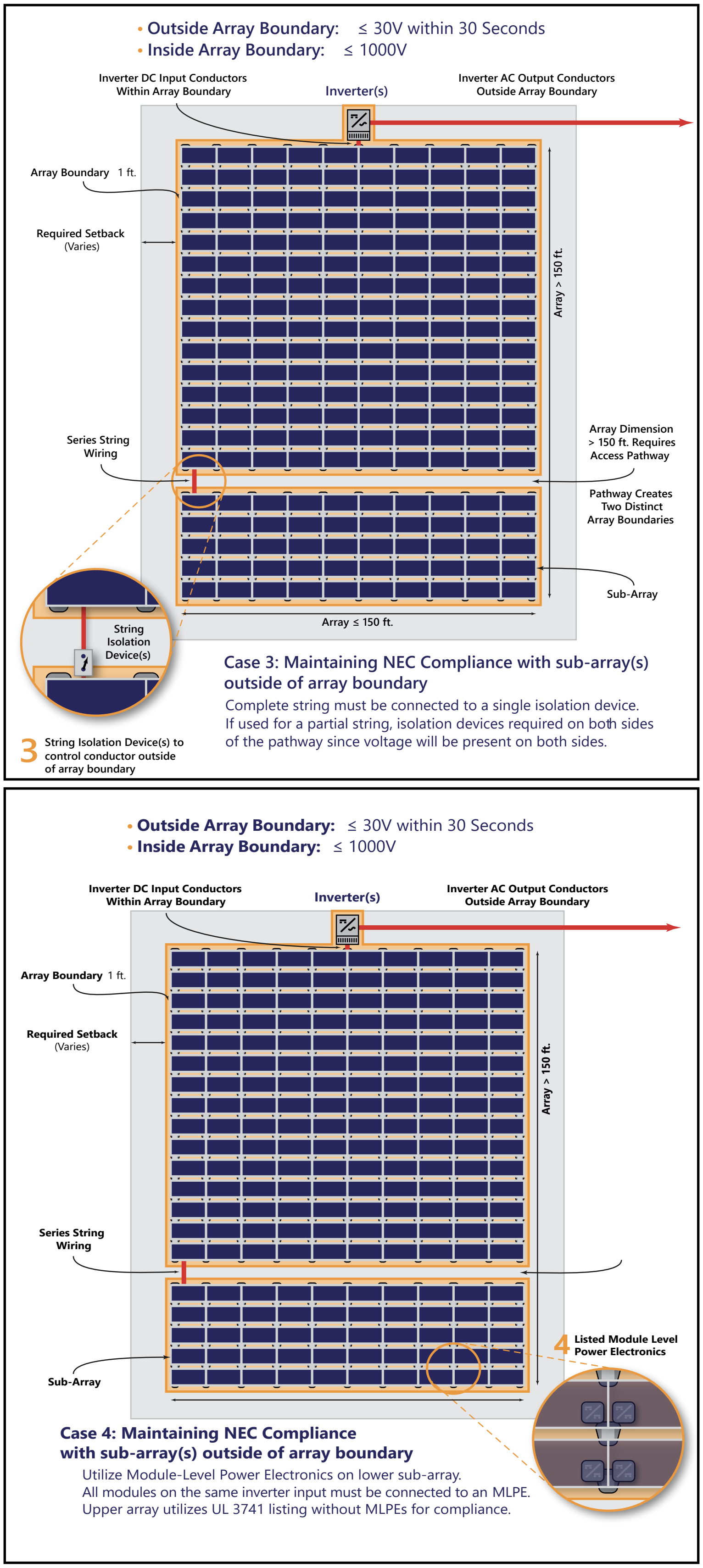


Figure 3: Racking Manufacturer Instructions for PVRSE on PV Sub-arrays

Image Source – Citation 8

DC-Optimized Solution: SolarEdge PVHCS at 125V Max

UL 3741 compliance is built into all SolarEdge optimizers and inverters, requiring no extra parts. This solution, referred to from this point on as "DC-optimized", consists only of optimizers and inverters, and can be used in combination with any PV modules and any racking.

The DC-optimized solution removes the hazardous energy by lowering voltage within the array to a maximum of 125VDC (open circuit voltage of 2 modules in series). As a result, these systems fall within hazard levels 0-1 (under UL 3741) inside the array boundary, eliminating the need for additional protective measures to comply with UL 3741. The solution maintains design flexibility, with no need for special racking, raceways, wire management, guards, module combinations, inverter collocation, etc.

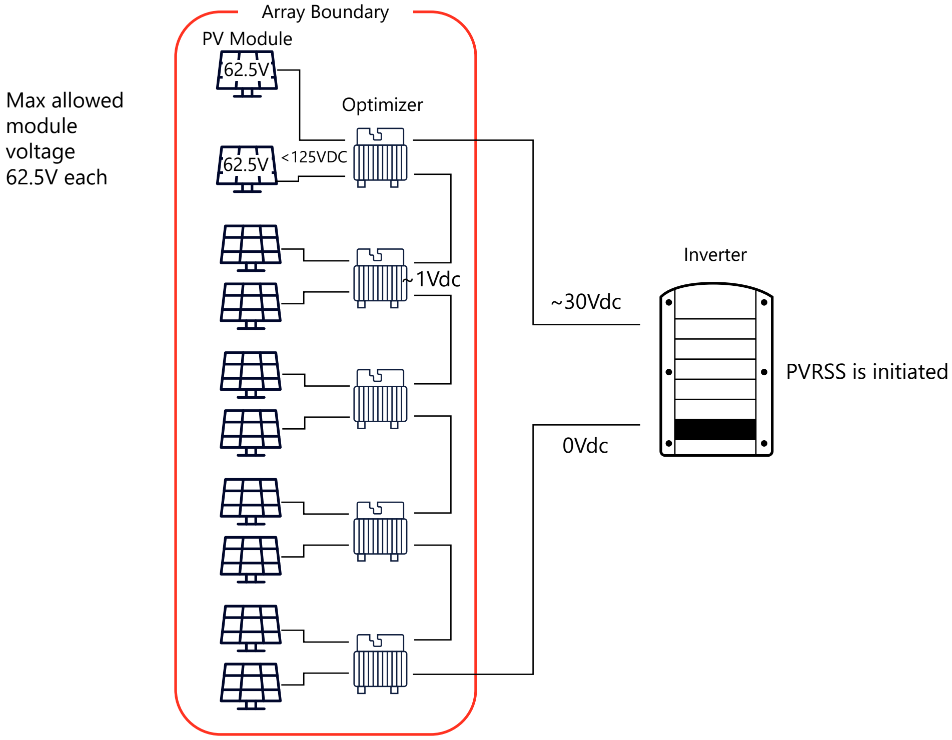


Figure 4: SolarEdge UL 3741 Solution Diagram

Balance of System (BoS)

A number of entities in the industry claim that the opportunity to eliminate MLPEs will reduce system costs. While the SolarEdge DC-optimized solution offers enhanced safety over non-DC-optimized solutions, the elimination of MLPEs might not actually offer the cost-savings expected. Due to the design constraints of UL 3741 compliance, the balance of system costs for a non-DC-optimized solution can be considerably higher than for a DC-optimized solution, which can offset the increased cost of optimizers.

Five typical rooftop C&I PV systems of various sizes were designed in two variations to be NEC 2020 and UL 3741 compliant. One using a SolarEdge DC-optimized solution and one using a non-DC-optimized racking solution. Three of these systems (1.5MW, 2MW and 5MW) have undergone review and verification by Pure Power Engineering, and the approaches employed for the calculation of BoS costs for the remaining two (300kW, 1MW) have also received validation from Pure Power Engineering.

BoS Costs Estimated

The BoS costs for a project utilizing a non-DC-optimized solution can be estimated and compared to an equivalent DC-optimized system, with modelling tools such as helioscope and CAD. This process was repeated for multiple projects, ranging in size from 300kW to 5MW DC to estimate cost differences between DC-optimized and non-DC-optimized designs.

The electrical BoS cost savings for various projects comparing a DC-optimized against non-DC-optimized solution are shown in Figure 5 below. BoS cost estimates include:

- DC Materials – String homerun cabling, DC combiner boxes, fuses, grounding conductors, conduits, UL 3741 required array wire management components and PVRSE.
- DC Labor – Install costs for all components above and install costs for any MLPEs in the system.
- AC Materials – AC homerun conductors, grounding conductors, conduits, AC combiner boxes, panelboards, switchboards, circuit breakers, disconnects, and transformers.
- AC Labor – Install costs for all components above and install costs for inverters in the system.

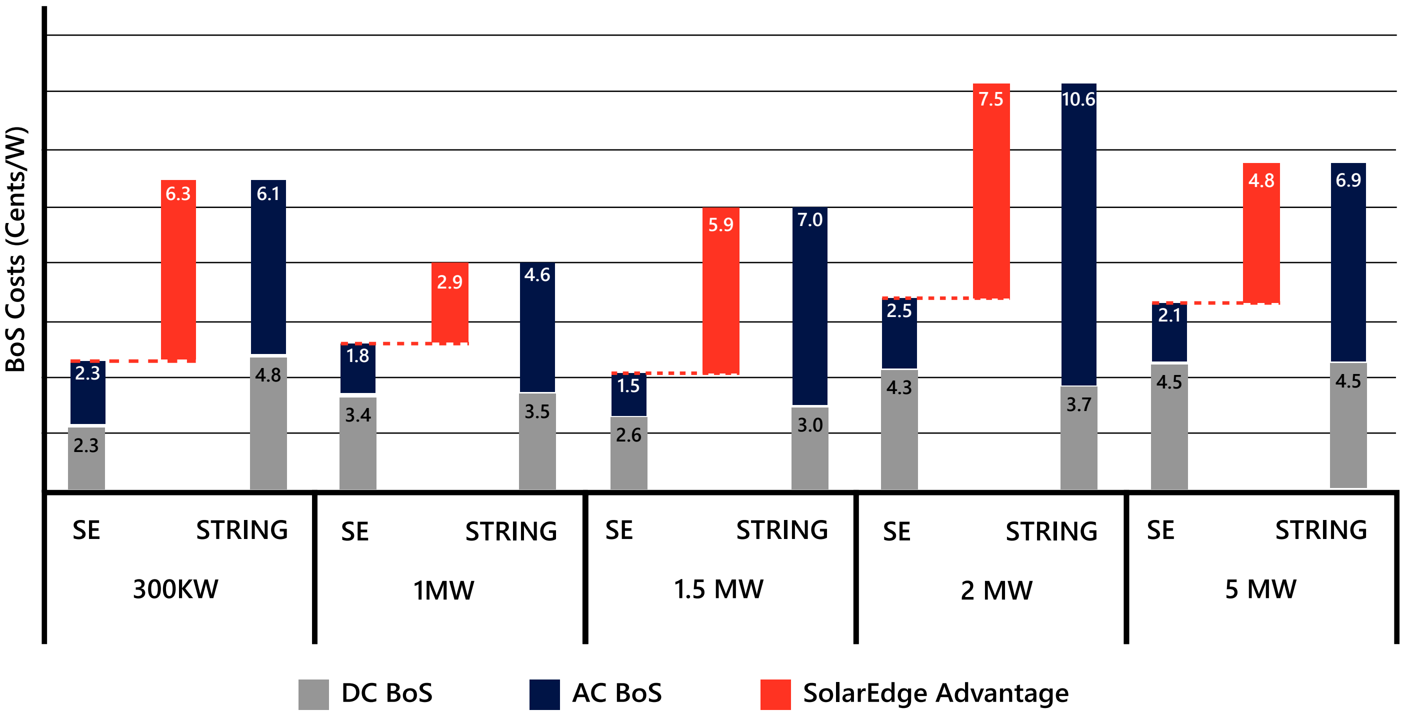


Figure 5: Electrical Balance of Systems Savings with DC-optimized Solution (Cents/Wdc)

As shown in Figure 5, savings of over 50% on electrical BoS are possible with a DC-optimized system. Three specific factors are responsible for the increased CapEx costs of a non-DC-optimized system at 1000VDC, the following sections explain in detail how these compliance requirements increase costs.

[1] SolarEdge commissioned Pure Power Engineering Group for a review of these system comparisons. The BoS calculation methods and results have been independently validated by Pure Power Engineering group.

AC BoS Costs Increased for Longer AC Cable Runs

For non-DC-Optimized systems, inverters must be installed within 1 foot of the array boundary. In larger systems with multiple arrays, the inverters become distributed throughout the rooftop. Distributed inverters will be further from the AC interconnection point (or AC switchgear), needing longer AC cable runs and leading to increased BoS costs, even when using aluminum conductors. To avoid too much AC voltage-drop, longer distance inverters often require an increase in cable gauge, or the addition of parallel cable sets, all of which increase the cost.

The distances from inverters to an interconnection point (or AC switchgear) can be compared between the same rooftop PV systems, using both non-DC-optimized and DC-optimized solutions. Conductor and conduit sizing is determined for both systems to follow NEC rules and to ensure a maximum AC voltage drop of 2.5%. Given the calculated distances and known costs for conductors and conduit, it is simple to estimate material and labor costs.

Average estimated BoS cost increase for longer AC cable runs from collocated inverters = **4 – 5 ₵/W**

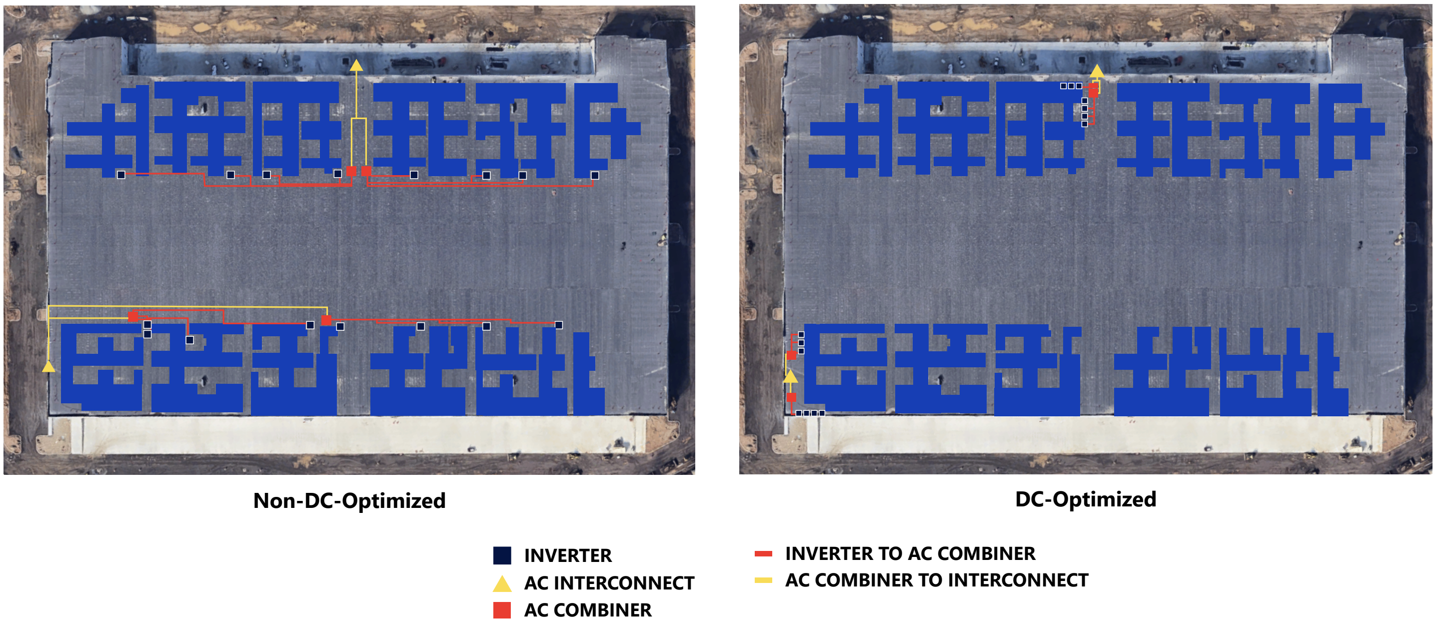


Figure 6: Example of AC Cabling Differences between UL 3741 non-DC-optimized and DC-optimized Solutions

PV Array Wire Management and Accessories:

A non-DC-optimized solution at 1000VDC requires that no wires are exposed between PV modules and that wires beneath modules must be routed to avoid contact with metal surfaces. The racking accessories and wiring techniques employed add costs both in materials and labor for the non-DC-optimized system. The Table below shows the specified cable management techniques for various racking manufacturers that have a UL 3741 listing.

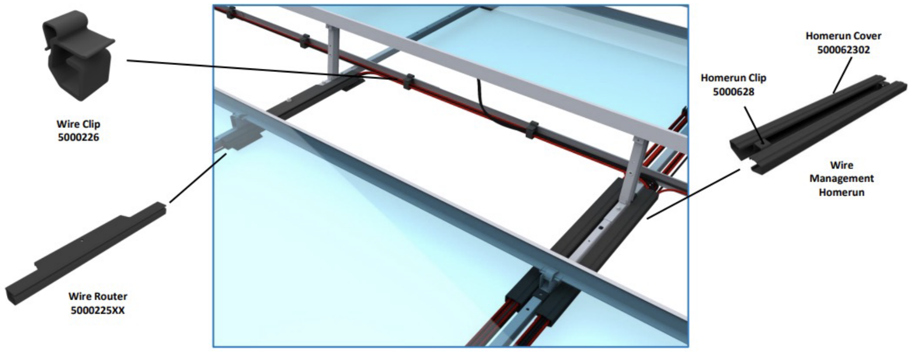
<table>
<tr><th>Make</th><th>Model</th><th>Cable Management Strategy</th></tr>
<tr><td>PanelClaw</td><td>clawFR</td><td>

Figure 7: PanelClaw Wire Management Requirements
Image Source - Citation 6</td></tr>
<tr><td>IronRidge</td><td>BX System</td><td rowspan="2">
Examples of wire installation under module frame

Examples of wire installation under Chassis.

Examples of wire installation in approved wireways

Figure 8: IronRidge or Sollega Wire Management Requirements
Image Source - Citations 8 and 9

*Note: Sollega and IronRidge UL 3741 system installation manuals use the same image set for wire management.</td></tr>
<tr><td>Sollega</td><td>FR510</td></tr>
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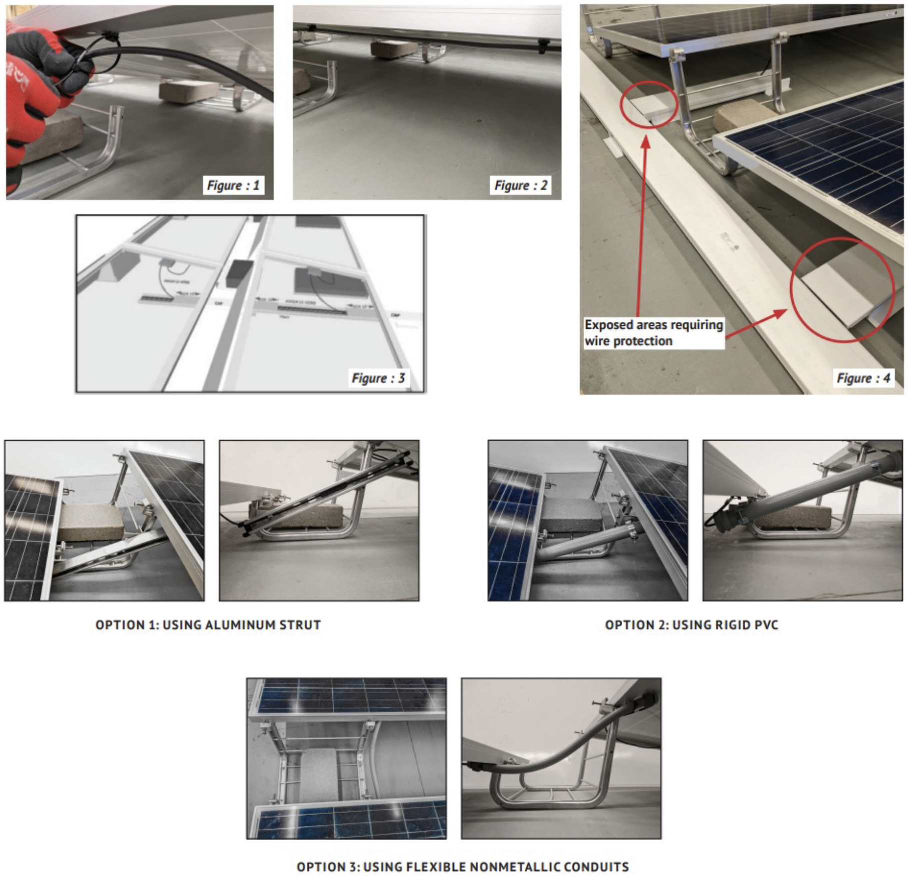
Make	Model	Cable Management Strategy
Unirac	RM10 Evo RM10 Legacy RMDT RM5 ECOFOOT 2+ ECOFOOT 5D GRIDFLEX 5	 Figure 9: Unirac Wire Management Requirements Image Source - Citation 7

Table 1: PV Array Wire Management requirements for non-DC-optimized solutions at 1000V

The prevailing racking solution wire management methods are used for estimating the additional costs on a non-DC-optimized system. At two wire clips per module, one wire router per row crossing of a string, and one homerun cover per row, all that is needed to estimate a total count is a string layout drawing. After completing such a drawing, determining a total cost for wire management components is simple. The costs for each component are estimated as:

- Wire Clip: Material – $1.00/pc. Labor – 100pc/hour.
- Wire Router: Material – $12.00/pc. Labor – 60pc/hour.
- Homerun Cover: Material – $20.00/pc. Labor – 50pc/hour.

Average estimated BoS cost increase for PV Array Wire Management and Accessories = **1 – 1.5 ₵/W**

Rapid Shutdown Equipment for Strings Crossing Multiple Array Sections

When PV strings extend across a gap of at least 2 feet between array sections, listed PV rapid shutdown equipment (PVRSE) must be employed for the system to remain NEC compliant. Except for small systems, it is near impossible to design a PV array that has no 2-foot gaps between array sections. If rooftop obstructions are not enough to require gaps between sub-arrays, the fire code requirements for 4-foot-wide walkways every 150-feet of array will make such gaps mandatory on almost any system over 300 kW DC. The only other way to avoid strings that cross arrays, would be to eliminate PV modules and sacrifice on energy production.

Non-DC-optimized systems give the same options for rapid shutdown beyond the inverter collocated arrays:

- Move all sub-arrays to be within 2 feet of the nearest array section.
- Use PV rapid shutdown equipment (PVRSE) for conductors that span the array gap. Complete strings can be connected to a single PVRSE device, partial strings require PVRSE on each side of the array gap as voltage will be present on both sides.
- Use MLPEs on all modules that are in the sub-array.

With a full system string layout, strings or homeruns that cross 2-foot array gaps can be identified. After deciding between PVRSE or MLPEs, simply total the number required for the system to remain UL 3741 compliant. The costs for each component are estimated as:

- PVRSE (2 strings Max): Material – $200/pc. Labor – 1pc/hour.
- PVRSE (8 Strings Max): Material – $1200/pc. Labor – 1pc/hour.
- Module level rapid shutdown device (2-to-1): Material – $35/pc. Labor – 25pc/hour.

Average estimated BoS cost increase for PVRSE on strings crossing multiple sub-arrays = **0.5 – 1 ₵/W**

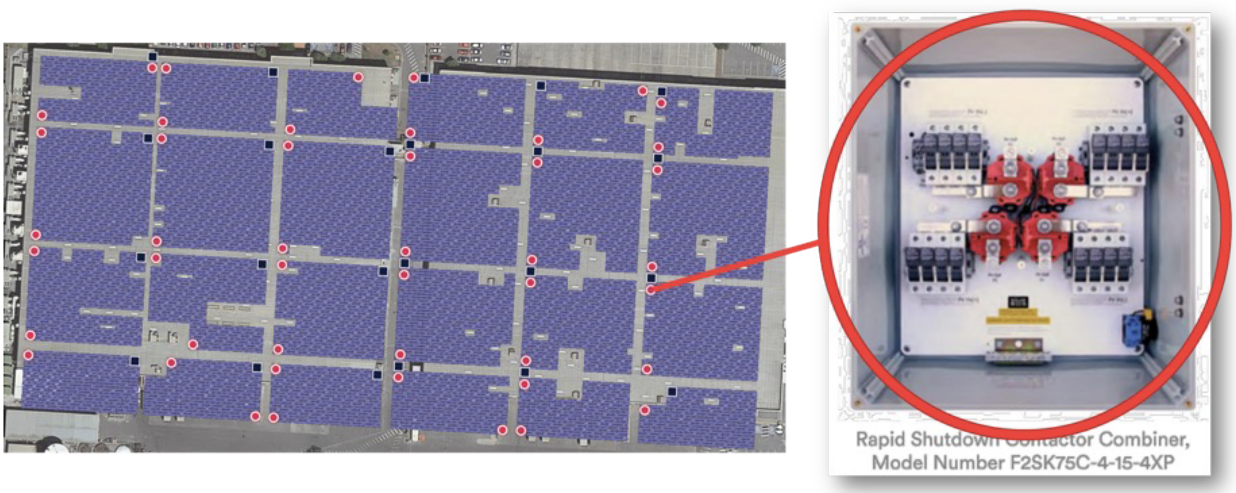


Figure 10: Example of Required PVRSE for Strings Crossing Array Gaps (5MW Rooftop Array)

Image Source – Citation 10

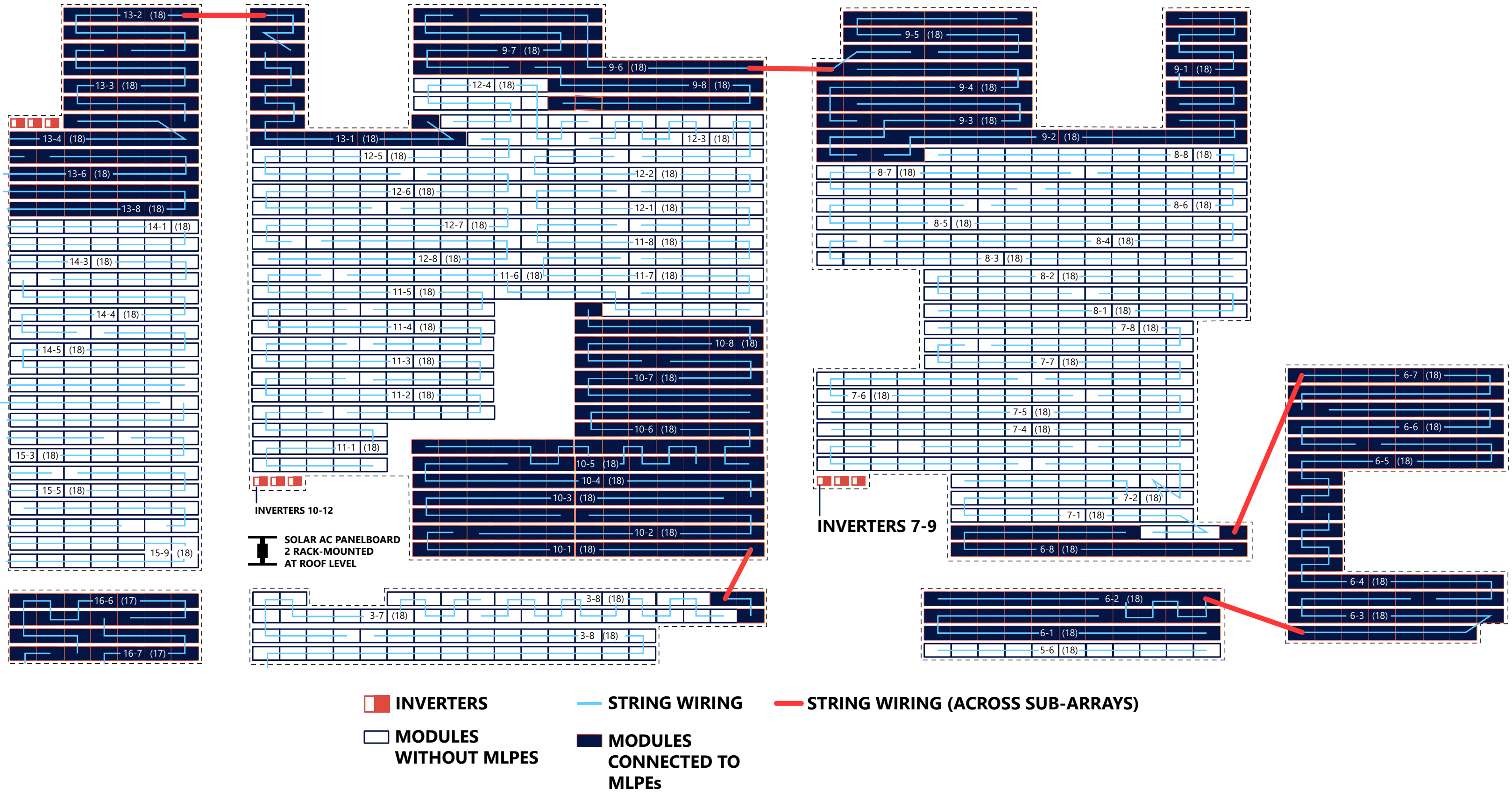


Figure 11: Example of Module Level RSDs (required on highlighted modules) for Strings Crossing Array Gaps

Operations and Maintenance Costs

Operational expenses (OpEx) also need to be considered when choosing a UL3471 solution. DC optimization provides continuous and granular data which enables real-time remote monitoring of potential issues at the PV array. Automatic RSD self-tests every day allow system owners to know in advance of issues on site, before they develop into larger and more costly concerns.

In non-DC-optimized systems without these capabilities, a site visit or other costly measures would be required to investigate issues. To ensure the long-term safety of non-DC-optimized systems using passive mechanical components, aging tests, visual inspection, and robustness testing should be implemented to maintain UL 3741 compliance over the lifespan of the system. Due to the complexity and inherent risks involved in maintaining non-DC-optimized solutions, senior technicians are often required, resulting in higher labor costs.

The estimate of additional O&M costs for non-DC-optimized systems includes:

- IV-curve testing – $1000/MWDC/occurrence – This practice is typically used only when production issues occur. As such the likelihood for this cost occurring at any point of the system's life is best modeled using a bath-tub curve.
- Infrared scanning and connector inspection – $1000/MWDC/occurrence – This practice is typically used only when production issues occur. As such the likelihood for this cost occurring at any point of the system's life is best modeled using a bath-tub curve.
- Annual drone/aerial inspection and report – $800/MWDC/year.
- UL 3741 compliance array safety inspection walkthrough – $1000/MWDC/year.
- Increased truck rolls from less granular monitoring and more time on site – $1000/MWDC/year.

The model for increased O&M costs per year is shown below in Figure 12. Net-present-value estimates for the increased O&M costs over system lifetime were calculated using an inflation rate of 3% and a discount rate of 6%.

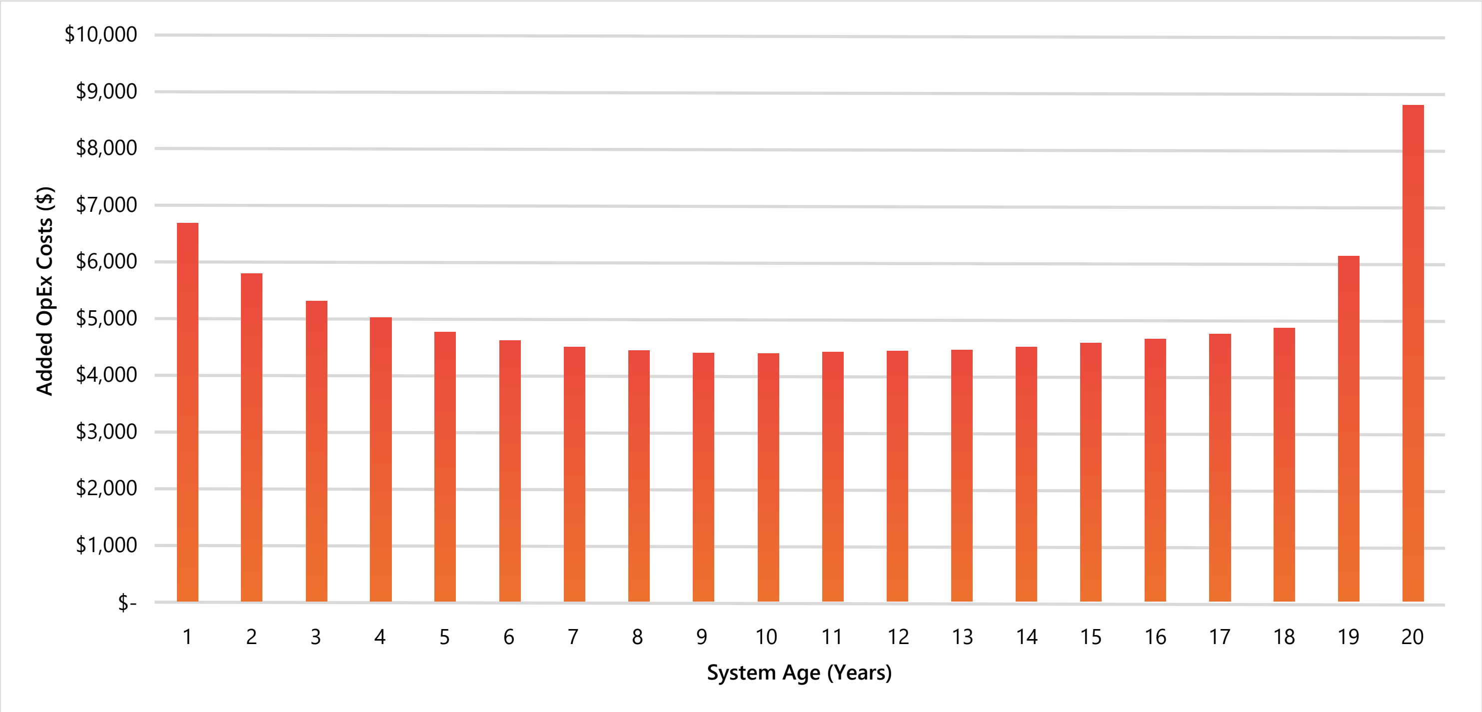


Figure 12: Increased O&M Costs (per year) for Non-DC-Optimized Solutions (in a typical 1MWdc system)

Over a 20-year lifespan, the estimated cost increases for O&M on non-DC-optimized systems are valued at **5-6 ₵/W** (NPV).

SolarEdge Production Advantage

Another benefit to using SolarEdge DC-optimization solutions is the improved energy production, resulting in potential greater revenues over the PV system lifespan. The value of module-level MPPT over string-level MPPT can be simulated using PVsyst to estimate the yearly energy production for first and last year of the system life. By reducing mismatch losses and improving bifacial gains (when applicable) DC-optimized systems consistently have an increased lifetime production.

The graph below demonstrates the net present value (NPV) revenue gain of a DC-optimized system compared to an equivalent non-DC-optimized system. The revenue gain calculations assume an electricity rate of 12₵/kWhr, an annual escalator of 3%, and discount rate of 6%.

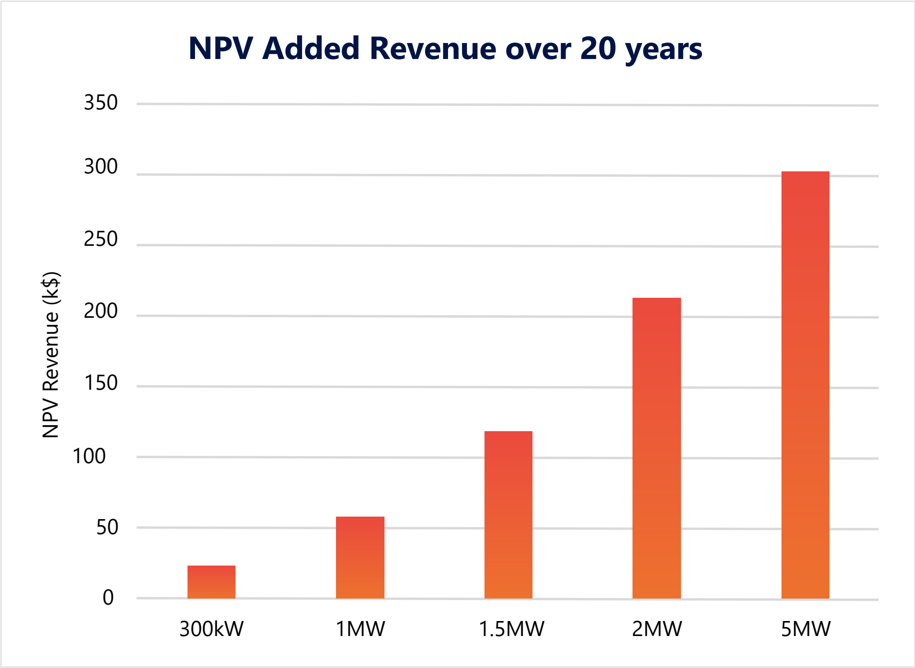


Figure 13: Energy Production Revenue Increases with SolarEdge

The average estimated revenue increase (across a 20-year lifespan) for all compared projects is **7 - 8 ₵/W** (NPV).

Five typical rooftop C&I PV systems of various sizes were designed in two variations to be NEC 2020 and UL 3741 compliant. One using a SolarEdge DC-optimized solution and one using a non-DC-optimized racking solution. Three of these systems (1.5MW, 2MW and 5MW) have undergone review and verification by Pure Power Engineering, and the approaches employed for the calculation of BoS costs for the remaining two (300kW, 1MW) have also received validation from Pure Power Engineering.

[2] SolarEdge commissioned Pure Power Engineering Group for a review of these system comparisons. The production simulation methods and results have been independently validated by Pure Power Engineering group.

Summary of Benefits With SolarEdge

Upon a full review and comparison of UL 3741 compliant solutions, there are several advantages to using a DC-optimized solution instead of a non-DC-optimized solution at 1000VDC:

- Safety – With voltage designed to automatically reduce to touch-safe level upon detecting faults or maintenance actions, the system provides enhanced safety for firefighters and other personnel who may be working on or around the PV array. While hazardous voltage (up to 1000VDC) remains present in a non-DC-optimized system, DC-optimized solutions leverage daily RSD self-test, SafeDC, and other features to remove human error from the equation of safety.

- Balance of System costs – With SolarEdge equipment and far fewer design restrictions to remain NEC compliant, developers and owners can achieve up to 50% savings on electrical BoS.

- O&M Cost Reduction – DC optimization allows for real-time system monitoring and daily RSD self-test, avoiding the need for walk through inspections, drone flyovers, IV curve tracing, and other costly O&M techniques. Additionally, non-DC-optimized solutions rely on passive mechanical components. To be considered compliant with UL 3741, the mechanical components are inspected only at installation. Without regular inspection, testing and repair, these components are likely to fall out of the compliance standard after some time of operation, and therefore will offer little benefit to fire fighters.

- Energy production – Leveraging module level MPPT can provide up to 5% energy revenue gain over a 20-year lifespan on the system.

- Design flexibility – Inverters can be installed at a central location or at ground level while allowing for short AC runs to maximize savings and improve serviceability. Array can be broken into many sub-arrays without additional system components to remain UL 3741 compliant. Less restriction on viable locations for module placement means a larger system size can be installed, thereby potentially increasing energy production and return on investment for the system.

- Installer simplicity – non-DC-optimized solutions require a time-consuming installation process for the PV array, where highly precise wire management is necessary to make a compliant system. When NEC compliance relies on human execution and not automated features, potential errors are more likely to occur, which could lead to a failed inspection and unsafe system.

- Structural engineering simplicity – Accounting for the point-loading and additional reinforcement on a rooftop system for multiple inverter locations next to the PV array, can be much trickier and more expensive than for a single central location. If inverters are mounted at ground level, no additional structural reinforcements are needed.

Full System Comparison: CapEx, OpEx, and Energy Revenue

When taking all the above benefits into account, the choice to use DC-optimized solutions for UL 3741 compliance is clear. Using a market research average of 7 ₵/Wac cost for inverter equipment, a final estimate of all the capital expenses, including price of equipment (inverters and optimizers), electrical balance of systems, and direct labor, shows that DC-optimized and non-DC-optimized solutions are very similar in cost.

Under this analysis, CapEx for non-DC-optimized solutions are more expensive in 3 of 5 systems when compared against SolarEdge DC-optimized solutions.

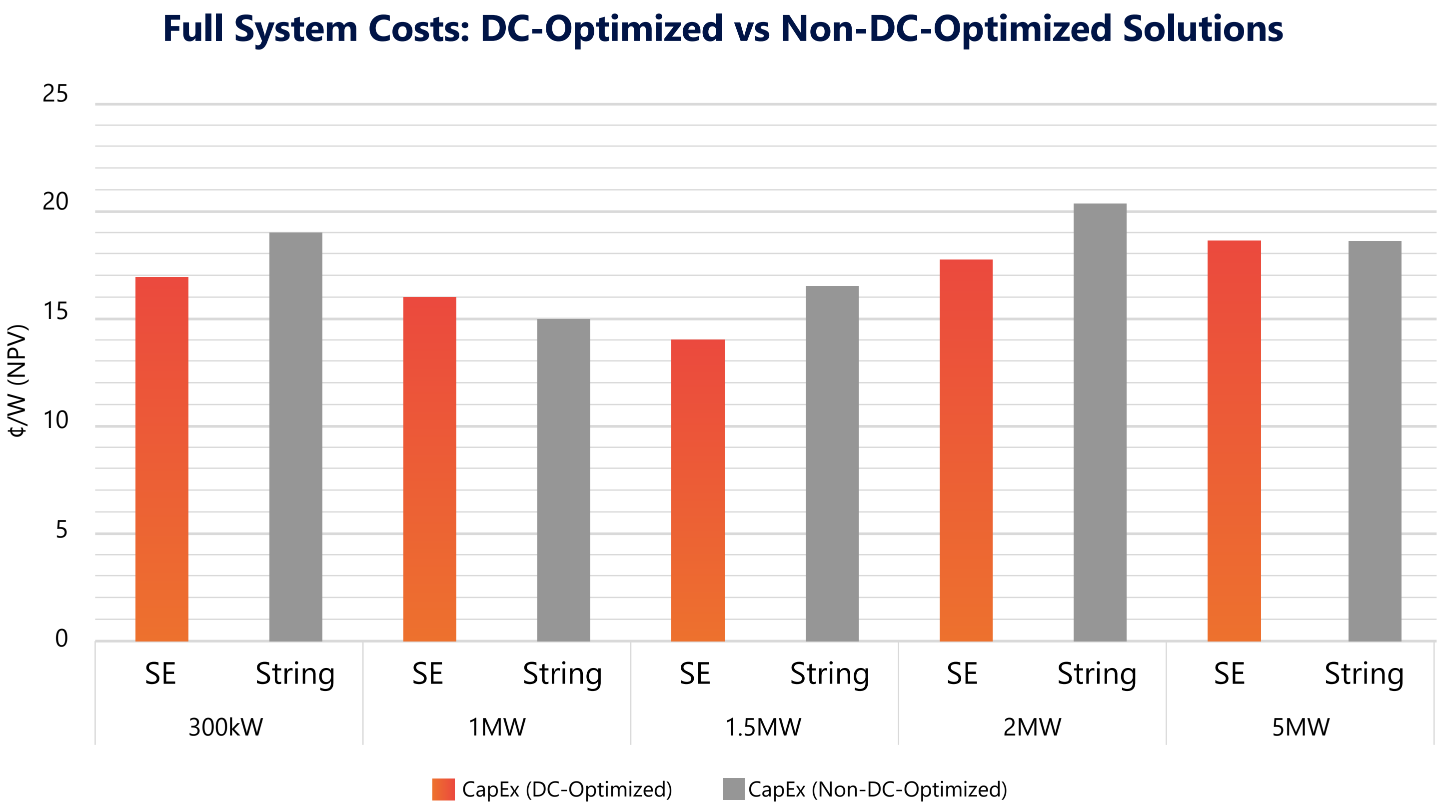


Figure 14: Cost Comparison of DC-optimized and non-DC-optimized Solutions (CapEx only)

When including an estimate of the additional OpEx costs for a non-DC-optimized system's full lifespan, the overall cost leans even more heavily in favor of utilizing DC-optimized solutions.

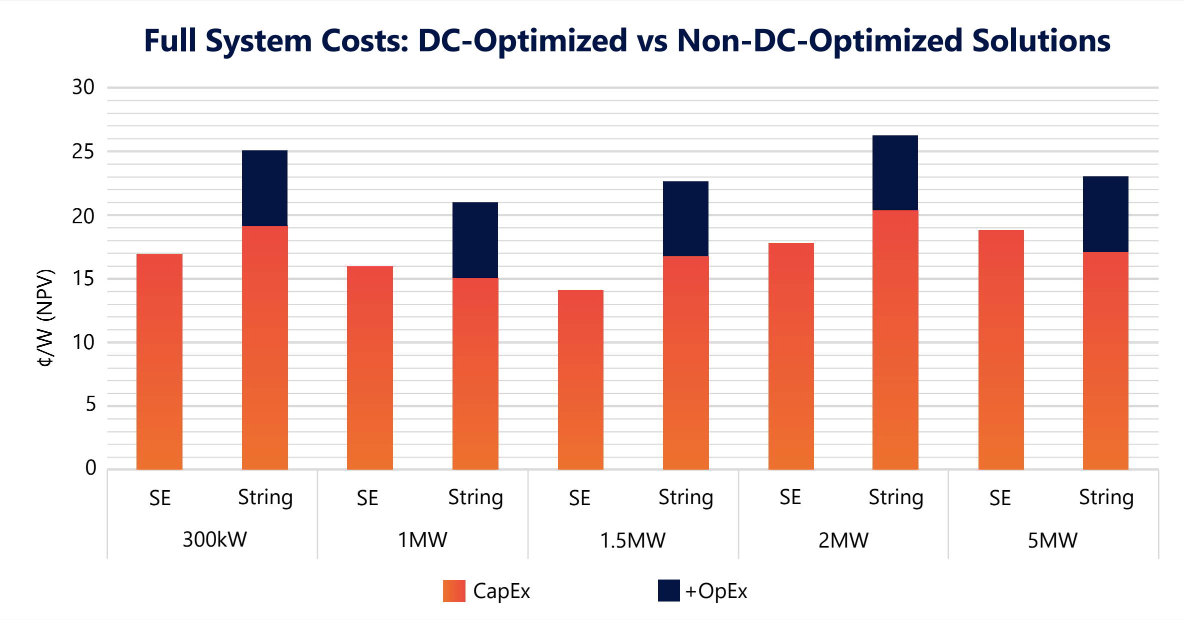


Figure 15: Cost Comparison of DC-optimized and non-DC-optimized Solutions (CapEx + OpEx)

Finally, when including the difference in expected energy revenue over a full lifespan as an offset to system costs, the economics for DC-optimized solutions are superior to that of non-DC-optimized solutions.

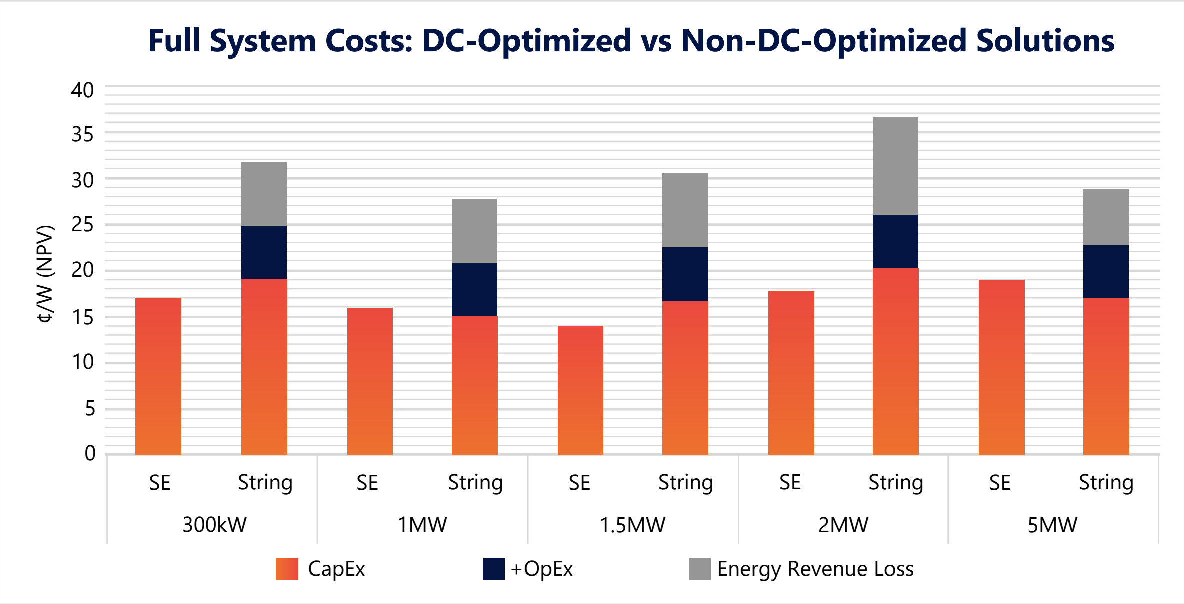


Figure 16: Cost Comparison of DC-optimized and non-DC-optimized Solutions (CapEx + OpEx + Energy Revenue Loss)

Conclusion

Prior to the introduction of UL 3741, the solar industry relied on MLPE technologies, including DC-optimization, to provide rapid shutdown. While the number of possibilities for rooftop rapid shutdown has increased with UL 3741 allowing non-DC-optimized systems, these options may not be beneficial to system owners in the way they might seem.

While SolarEdge DC-optimized solutions offer an enhanced safety environment for firefighters and other personnel, the perceived economic benefit of leaving MLPEs out of a PV system is an attractive proposition for many. However, upon further analysis, it appears that the estimated overall costs for a PV system over 20 years are lower using a DC-optimized solution.

From increased BoS costs, to increased O&M costs, to decreased energy revenues, non-DC-optimized solutions are hiding plenty of additional expenses, that will be felt by project stakeholders in addition to the safety concerns that are present. DC-optimized solutions remain the safer and more cost-effective option for meeting NEC rapid shutdown requirements throughout the lifetime of a PV system.

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