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Improving Bolted Joint Reliability in Utility-Scale PV

Gaps and Improvements in Tightening Methods, Tools, and Fasteners

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1. Introduction

A typical utility-scale solar photovoltaic (PV) site comprises hundreds of thousands of mounting structures, each containing multiple bolted joints, resulting in millions of joints across the site (see Figure 1). Many of these joints are part of the structural load path, transferring static loads (dead load, snow) and dynamic loads (wind) from the PV modules to the foundation. In some mounting structures, these joints also serve as part of the grounding system, providing an equipotential, low-resistance electrical bond between the exposed conductive components of the mounting structure.

Whether a bolted joint is in the structural load path or serves as part of the grounding system, its performance depends on the pretension applied during installation. The resulting clamp load holds the joint together and resists separation and lateral movement between connected components. A lack of control of pretension can result in joint slipping, opening, fastener fracture, or loss of electrical bond, undermining both structural integrity and electrical safety.

This report classifies bolted joints in PV mounting structures into two broad groups: traditional structural joints and alternative structural joints. Traditional joints mirror the types of connections used in steel-framed buildings and bridges, where thicker steel or aluminum members are joined with ½-inch or larger bolts.

Alternative joints, by contrast, are designed for thin-gauge cold-formed steel, aluminum extrusions, stamped parts, and various proprietary clamps or clips. These connections often rely on fasteners smaller than ½ inch in diameter, such as stainless steel screws and proprietary designs.



Figure 1: A typical utility-scale solar photovoltaic (PV) site consists of hundreds of thousands of identical mounting systems, each containing multiple bolted joints, amounting to millions across the site.

While well-established codes and standards exist for traditional structural bolted joints, they are rarely applied in the PV industry. For alternative structural bolted joints, there are no unified standards. As a result, fastener choices, installation methods, and tightening tools remain unstandardized across utility-scale solar PV mounting structures. Practices vary widely across mounting structures, and in many cases, pretension is poorly controlled, highlighting a critical gap in current practice and motivating this report.

This report will focus on identifying gaps and improvements needed for fastener selection, installation methods, and tightening tools for bolted joints in utility-scale solar PV mounting structures. It will highlight where practices and standards developed for conventional structural bolted joints can be applied directly and where new guidance, tightening methods, tools, and

fasteners are needed to ensure predictable joint capacity.

2. Clarification of Terminology

In the utility-scale solar PV industry, multiple overlapping terms are used to describe the structures and components that support photovoltaic (PV) modules. These terms often overlap or differ depending on whether the context is structural design (e.g., ASCE guidance) or product safety and evaluation (e.g., UL 2703). This report adopts the following simplified terminology:

Mounting structure: The engineered physical framework that supports PV modules and transfers structural loads to the foundation. It includes ground-mounted fixed racks, trackers, and related support components. The usage aligns with the structural design perspective described in the ASCE Manual of Practice but is applied here as a general description across all system types.

Module attachments: These are the connection points between PV modules and the mounting structure. It includes clamps, bolts, brackets, and other devices used to retain and secure modules. In this report, the term encompasses both structural connections (as considered in engineering design) and UL-recognized devices (such as clips or retention hardware used in bonding and grounding).

Mounting system: This term refers specifically to UL 2703-listed products. A mounting system includes the complete racking assembly evaluated for mechanical strength, bonding, grounding, and retention. It consists of the rack, module mounting means, and rack mounting means, as defined by UL 2703.

3. Current State: Tightening Methods, Tools, and Fasteners

This section reviews the current tightening methods, tools, and fasteners typically used in utility-scale PV mounting structure bolted joints. It examines shortcomings in common practices and tightening tools that can lead to large variations in pretension and joint capacity. Compounding this are vague or incomplete fastener specifications and variations in tightening practices across the industry. By outlining these challenges, this section sets the stage to discuss improvement opportunities.

3.1 Torque Control Tightening Method

Across the solar industry, bolted joints are almost universally tightened using torque control, a method in which a specified torque is applied to achieve the desired pretension in the fastener. As the nut or bolt head is turned, the fastener stretches slightly, much like a spring. This elongation produces bolt pretension, which generates the clamping force that holds the connected components together (see Figure 2).

When torque is applied, only a portion of the torque contributes to pretension. Roughly half is lost to friction beneath the turning head or nut, about forty percent is consumed in the threads, and only the remaining ten percent stretches the bolt to create clamping force (Bickford, 2007).

Because of this distribution, the relationship between torque and pretension is strongly influenced by surface condition, coatings, and lubrication. So even minor changes can affect the clamp load achieved at a given torque setting.

PV mounting system and module installation manuals typically outline assembly procedures and, in some cases, specify torque values for each fastener. After the joints are tightened, a torque audit is often conducted to confirm they meet the specified values before commissioning. Any fasteners found out of specification are adjusted and rechecked until they comply.



Figure 2: Typical utility-scale solar PV construction site. The bolted joints in the PV mounting systems are almost universally tightened using the torque control tightening method.

Torque control tightening is widely used because it is simple, fast, and relatively inexpensive, but unfortunately, the resulting pretension can vary widely due to friction, tool selection, and operator technique.

3.1.1. Shortcomings of Torque Control Tightening

Although specifying a torque value is common for fasteners in PV mounting structures, conventional structural bolting applications such as building and bridge steelwork have largely moved away from torque-based tightening. Instead, they generally use methods and fasteners that are less affected by variations in fastener friction and that produce a known, controlled pretension, such as twist-off-type tension-control bolts or direct tension indicator (DTI) washers (RCSC, 2020). Both methods provide a visual indication that the minimum pretension was achieved during tightening, making it much easier to audit the joints after tightening.

That shift reflects the long-standing understanding in structural bolting that torque is an unreliable proxy for pretension. Long-standing experimental studies beginning in the 1950s demonstrated that identical tightening torque can produce widely varying clamp loads because most of the applied torque is dissipated by friction in the threads and under the turning element, rather than converted into bolt stretch (Bickford, 2007) (RCSC, 2020). As this understanding matured, structural bolting guidance increasingly limited torque-based tightening to tightly controlled procedures.

In solar PV mounting structures, torque-controlled tightening remains the default method, but it inevitably leads to unpredictable pretension and joint capacity. Even a perfectly calibrated tightening tool cannot ensure consistent pretension unless fastener friction and installation conditions are also controlled (see section 3.3 Current Threaded Fastener Specification). This risk is compounded when PV mounting system and module installation manuals state a torque value without the desired pretension, leaving crews and inspectors to treat torque as the objective rather than a means to achieve the pretension.

These gaps in how torque is specified and understood become even more apparent when you look at the tools used to apply it. Because installation manuals rarely identify a specific tightening method or tool type, crews often rely on whatever equipment they judge suitable for the torque level and production needs of the project. This creates a wide range of field practices and levels of control. The next section examines the tightening tools commonly used on PV sites and how their capabilities and limitations shape the consistency of bolt pretension.

3.2 Current Tightening Tools

Mounting system and module installation manuals from manufacturers seldom identify a specific torque control tool by model or style. This leaves tool selection to the EPC or contractor, typically based on the required torque, the level of accuracy needed, installation speed, and budget limitations.

Dan Schmidt, Clean Energy Account Representative at Rhino Tool House, explained that the decision depends on the torque level, the tightening torque tolerance, and the number of fasteners to be tightened. In many cases, crews rely on cordless impact wrenches to tighten the nut until the joint is snug, with no visible gaps. This is followed by verification using a clicker-style torque wrench, after which the nut and threads are torque-marked.

When torque control is critical, Schmidt noted, high-volume applications such as module attachments, where the torque tolerance is often around ± 10 percent, EPCs tend to use right-angle nut runners, or an adjustable click torque wrench (Schmidt, 2025).

The tools available for torque application range from simple, inexpensive devices to advanced, high-precision systems. As illustrated in Figure 3 (the “Solar Tool Pyramid”), common field options span from impact drivers and impact wrenches at the base, up through shut-off impact wrenches and clicker-style torque wrenches/pulse tools, to precision slip-clutch nut runners and fully controlled nut runners at the top. All these tools serve the same basic purpose, but they differ markedly in accuracy, repeatability, and suitability for the demanding conditions of a utility-scale PV site. In general, moving up the pyramid increases control and consistency (and thus the likelihood of achieving a more uniform bolt pretension). But it also increases tool costs and the need for setup discipline, calibration, and maintenance, making tool choice a practical trade-off between joint criticality and project economics.

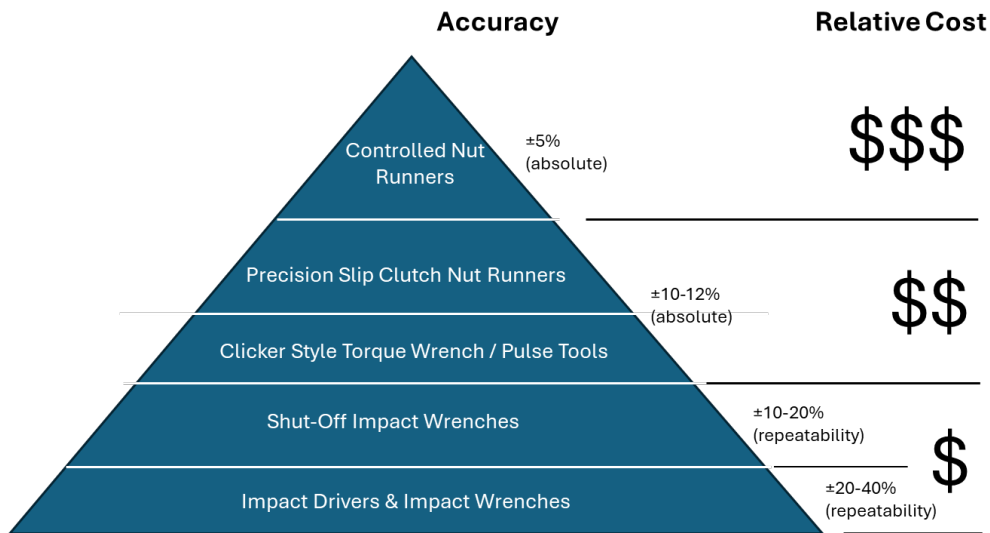


Figure 3: The Solar Tool Pyramid: Balancing cost and accuracy in torque tools used utility-scale PV construction sites.

3.2.1. Tightening Tool Types Currently Used at Utility-Scale PV Sites

Clicker-style torque wrenches are hand tools that apply specific torque to a fastener (see Figure 4). The wrench incorporates a calibrated spring mechanism that generates an audible and tactile "click" when the preset torque value is reached. This feedback indicates to the operator that the correct torque has been applied.



Figure 4: Example of an adjustable clicker-style torque wrench.

To achieve consistent results, it's important to grip the wrench at the proper location and apply a slow, even torque. Over-torquing may occur if the wrench is pulled after clicking. Habits, such as double-clicking, increase the chances of over-torquing. In practice, the actual accuracy achieved in the field, accounting for assembler behavior, is approximately ±10% with these types of wrenches (Bickford, 2007).

Clicker wrenches are readily available, lightweight, and affordable. However, they have some drawbacks, including operator fatigue, lower accuracy, and potential misuse due to inadequate training.

Impact drivers are power tools that deliver torque quickly through a series of rapid, concussive blows (see Figure 5). Inside the tool, a rotational hammer mechanism engages an anvil connected to the socket. As resistance in the joint increases, the hammer rides up a cam on

the anvil, compressing a torsion spring and storing energy. When the cam releases, the spring drives the hammer forward at high velocity, striking the anvil and transmitting a burst of torque to the fastener. This cycle repeats continuously as the hammer rotates, producing impacts at regular intervals.

Because the torque is delivered in short bursts, impact drivers generate very little reaction torque, sparing the assembler's hands and arms from the force typically felt with direct-drive tools. However, they produce significant noise and vibration, and the joint's stiffness strongly influences their performance. As a result, they cannot provide accurate or repeatable torque control and are best suited for applications where speed and versatility matter more than accuracy.



Figure 5: Example of impact driver.

Controlled impact wrenches operate on the same hammer-and-anvil principle as conventional impact drivers, but are engineered for greater tightening control, hence the name, controlled impact wrench, not impact driver. They deliver improved torque repeatability (not absolute accuracy), with a demonstrated repeatability of $\pm 15\%$ or better (Panasonic, 2026) (Milwaukee Tool, 2023). Improved repeatability comes from built-in sensors and control algorithms, with the tool performing the impact counting rather than the operator. These tools are typically trained on the actual joint in the field, so they can account for typical assembly variations such as misalignment and component fit. These tools are generally limited to fastener diameters of $\frac{1}{2}$ inch and smaller.

Controlled impact wrenches have been developed for the dusty, high-volume environment of utility-scale solar sites and are now commercially available (Fisher, 2024).

Slip-clutch nut runners are powered tools that rotate a nut or screw until the resistance reaches a preset torque value. Inside, a precision-machined gear train transmits torque from the motor to the fastener. When the target torque is reached, the slip clutch mechanism disengages the drive, preventing further rotation and reducing the risk of over-torquing. Under ideal conditions, these tools can achieve $\pm 10\%$ accuracy in calibrated torque and offer a straightforward, operator-friendly design (Bickford, 2007).

While well-suited for repetitive tightening tasks in controlled environments, current slip-clutch nut runners on the market are generally not built for the demands of high-volume assembly in dusty, outdoor PV construction sites. Dust ingress, temperature extremes, and long duty cycles can accelerate wear and degrade accuracy, making them less reliable without frequent maintenance.

Controlled nut runners take torque control a step further by incorporating precision gearing, torque transducers, and closed-loop electronic controls. During operation, they continuously monitor torque, speed, and angle, shutting off the motor the instant the preset torque is achieved. Many models also offer data logging and basic error-proofing functions, allowing quality tracking at the individual fastener level.

With absolute torque accuracy as low as $\pm 5\%$, controlled nut runners are among the most precise tools available for bolted-assembly applications (Bickford, 2007). This precision, however, comes with trade-offs. They are relatively expensive, require careful handling, and in many cases, are not engineered for dust, moisture, and temperature extremes common to utility-scale PV construction sites.

3.2.2. Shortcomings of Current Tightening Tools

At utility-scale PV sites, the hot, dusty, and often windy conditions create challenges for tightening tools, particularly those not designed for these environments. Dust and grit routinely find their way into clutches, gears, and sensors, leading to wear and gradual loss of calibration. High temperatures can accelerate lubricant breakdown, shorten battery life, and affect sensors like torque transducers, which can become sensitive to heat over time.

Precision tools, such as controlled nut runners, offer high torque absolute accuracy, typically within ± 5 percent, and include advanced features like data logging and error-proofing. However, these tools were generally designed for high-volume automotive manufacturing lines, where conditions are relatively clean, controlled, and repeatable. In the field, the environment is comparatively harsh. These tools are also relatively expensive and generally do not hold up well when exposed to dust, moisture, or sustained temperature extremes. As a result, the tools require careful handling and more maintenance than crews usually have time for.

Mounting system and module installation manuals rarely identify torque tools by model or type. As a result, contractors often rely on tool distributors for guidance; unfortunately, many distributors are not familiar with the conditions and requirements of utility-scale PV construction. Without prior experience in the solar market, their recommendations can easily miss the mark. As a result, EPCs and contractors often rely on more rugged, less expensive tools that lack error-proofing and are less precise. It is a trade-off that many crews accept because the simpler tools are tough enough to last through a project. In fact, some EPC firms now include full tool replacement in the budget for every new job. For them, tool wear is expected. It is part of doing business, even though it adds to the overall installation cost over time.

3.3 Current Threaded Fastener Specification

Threaded fasteners used in photovoltaic (PV) mounting structures and module attachments vary across manufacturers and designs. Most mounting systems rely on the familiar flange screws, hex cap screws, carriage bolts, u-bolts, nuts, and washers, generally in the $\frac{1}{4}$ - $\frac{1}{2}$ inch (M6–M12) range. Fasteners are commonly manufactured from low-carbon steel, heat-treated alloy steel, or stainless steel. If necessary, the fasteners are coated with hot-dip galvanizing, mechanical zinc, electroplated zinc, or zinc-flake finishes.

The critical properties of the fasteners, including material grade, tensile and yield strength, hardness, thread geometry, head style, and coatings, are frequently defined through established consensus standards (such as ASTM, ASME, SAE, and ISO). While many fasteners used in PV mounting structures conform to these standards, some mounting-system manufacturers procure or specify hardware without citing a particular standard, identifying only the fastener size and a general material description such as “stainless steel.”

Responsibility for specifying and supplying fasteners varies across the PV industry. Mounting-system manufacturers may provide the hardware directly or list the required components in installation manuals or EPC documentation. Module manufacturers rarely supply fasteners and often reference only a bolt diameter or general description in their manuals. When fasteners are not included with the system, procurement typically falls to contractors or EPCs, who source hardware based on the information available in project documents.

3.3.1. Shortcomings in the Specification and Field Control of Threaded Fasteners

Several gaps show up in how threaded fasteners are specified and managed on utility-scale PV projects. Most of these stem from the level of detail in the documentation, the consistency of the fastener properties, and the degree of control maintained from procurement through installation. The next subsections examine where these issues arise.

3.3.1.1 In-Complete Fastener Specifications

Detailed specifications for fasteners have historically been absent from PV module installation manuals, and as a result, the capacities of many fasteners are not well defined. For example, simply specifying a “5/16-inch (M8) stainless steel bolt,” as is common in PV module installation manuals, is woefully incomplete. Such a callout does not define key attributes such as yield strength, tensile strength, and thread fit, so bolted joint capacity is, frankly, unclear. The gap between laboratory validation and field performance becomes especially apparent when real-time tightening data is available. As Mike Madden of Rhino Tool House explains: “It’s possible to dial in the tightening process for a fastener in the lab, and everything works great. But if you get a bad batch of fasteners in the field and the tool shows an error, the first thing they think is that there’s something wrong with the tool. Well, the tool is doing what it should. It’s telling you that there’s something wrong with the process. The fastener properties are wrong.” (Madden, 2025)

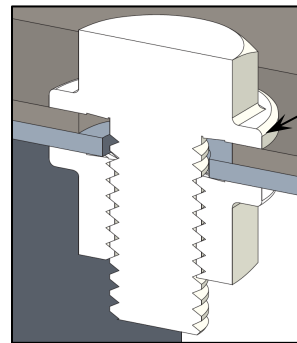
More complete fastener specifications typically would reference established fastener consensus standards from organizations such as ASTM, ASME, SAE, and ISO. Referencing these standards ensures that fasteners have defined and controlled attributes. In the absence of detailed fastener specifications, lower-cost fasteners with unknown mechanical properties are used. For example, common stainless-steel fasteners with markings such as “304” or “316” do not reference consensus standards; instead, they imply the material composition (see Figure 6). This is clearly a gap the industry should address.



Figure 6: Fastener marked 304 only identifies the metallic composition, not the mechanical properties

3.3.1.2 Lack of Field Control of Fasteners Friction

At utility-scale PV construction sites, keeping fasteners clean and protected is a persistent challenge. Fasteners are often subjected to dust, moisture, and rough handling long before installation, yet installation manuals and specifications rarely address storage, handling, or cleanliness requirements. Without consistent control from delivery through installation, variations in fastener friction are unavoidable, leading to inconsistent clamp loads even when torque-controlled tightening procedures are followed correctly (see Figure 7). Another gap the industry should address.



Contaminants, moisture, and corrosion can affect friction in the threads and the rotating bearing surfaces of the nut can result in unpredictable pretension.

Figure 7: Unpredictable friction results in unpredictable pretension when a threaded fastener is tightened using torque control tightening.

3.4 Summary of Gaps – Torque Control Tightening Method, Tools, and Threaded Fasteners

Tightening Method (Torque Control Tightening) Gaps

- Torque control tightening is the least accurate method for tightening threaded fasteners in the field and results in significant variations in pretension (i.e., joint capacity) unless both the tightening torque and fastener friction are tightly controlled at the solar PV construction site.
- Pretension requirements and tightening procedure details are often missing or unclear in PV mounting system and module installation instructions.
- There are opportunities to improve training on the nuances of torque-controlled tightening for solar PV mounting structure designers, contractors, and inspectors.

Tightening Tool Gaps

- PV mounting system and module installation manuals rarely specify tool type or model,

leaving contractors to make ad hoc selections and creating significant variability.

- Field crews often rely on rugged but imprecise workflows (e.g., impact wrench snugging followed by clicker verification), which lack error-proofing and yield inconsistent pretension.
- Harsh site conditions (heat, dust, wind) degrade tool performance: grit causes wear and calibration drift, while heat affects lubricants, batteries, and sensors.
- Precision tightening tools, such as controlled nut runners, offer high accuracy and error-proofing in a factory environment. Unfortunately, they are generally not built to withstand the harsh conditions of utility-scale PV sites. As a result, they require levels of care, calibration, and maintenance that field crews often cannot support. Truly ruggedized precision tightening tools, especially for fasteners under ½ inch, are not common in the PV industry.
- When installation manuals lack torque-tool guidance, contractors often turn to tool distributors. While some distributors have experience with utility-scale PV construction sites and can offer strong recommendations, others are still unfamiliar with the demands of utility-scale construction.

Threaded Fastener Gaps

- The lack of unified standards for mounting structure bolted joints results in inconsistent fastener choices, installation methods, and tool practices across projects and manufacturers.
- Fastener specifications are frequently incomplete or vague in some PV mounting system and module installation manuals, creating uncertainty about critical properties such as yield strength, tensile strength, washer geometry, etc.
- Poor field control of fastener cleanliness, handling, and storage (dust, moisture, rough handling) alters friction and undermines pretension, even when torque procedures are followed.

4. Immediate Improvement Opportunities

The shortcomings outlined in the previous section make it clear that, although torque-controlled tightening has limitations, it will remain the default tightening method for most utility-scale PV mounting structure joints for the foreseeable future. Contractors understand the method, the tools are readily available, and the speed of tightening fits the pace and economics of utility solar PV construction. As a result, the most practical gains over the next few years will come from tightening up how torque control is specified and implemented in the field. Improving the process we already rely on is far more achievable in the near term than replacing it.

Several developments already underway can help improve joint reliability without requiring a wholesale shift in industry practice. A recent revision to UL 2703 clarifies expectations for critical fasteners and introduces a statistical method of determining minimum clamp load. In parallel, the forthcoming ASCE/SEI Solar PV Structures Manual of Practice is expected to push the industry toward rational design practices and more consistent treatment of bolted joints across mounting structures.

There is also an opportunity to improve industry-wide understanding of torque-control tightening nuances through better education and more deliberate tool selection. Better collaboration among mounting system manufacturers, EPCs, contractors, and tool distributors would result in improved installation manuals and enable crews to achieve consistent mounting structure quality more easily.

These immediate improvements won't fill every gap. Still, they offer a practical way to improve the consistency of joint performance while the industry works to improve standards, tools, and fastener technology.

4.1 Adoption of ANSI/UL2703 June '25 Revision

A working group of consulting engineers, mounting system manufacturers, and UL representatives collaborated to update ANSI/UL 2703, resulting in the June 2025 revision. The changes clarify how to identify critical joints, make fastener requirements more consistent, and introduce new ways to manage clamp loads without relying only on torque (ANSI/UL, 2025). In the near term, mounting system manufacturers could begin to close some of the gaps identified in this report by adopting these revisions.

ANSI/UL 2703 is a product safety standard that evaluates PV mounting systems, clamping and retention hardware, and grounding/bonding components. A UL 2703 listing confirms that a manufacturer's mounting system or component has been tested against defined safety criteria. These criteria emphasize outcomes such as mechanical strength, material suitability, and electrical bonding and grounding.

The revised standard now includes two tiers. The first sets mandatory requirements for manufacturers seeking a UL 2703 listing. The second tier defines optional provisions that manufacturers may adopt to achieve tighter control of joint pretension or to qualify alternative fastening technologies. While adoption of these optional measures remains limited, manufacturers will need to update their practices as the industry moves toward broader compliance.

The revision recognizes that torque-controlled tightening will remain the standard approach. The focus, however, shifts away from simply asking "what torque was applied" to the more critical question of "what clamp load is required, and how can it be achieved consistently." This shift establishes clearer expectations for what must be defined, documented, and repeated reliably across large utility projects.

4.1.1. New Mandatory requirements for ANSI/UL 2703 listed mounting systems

- **Critical fasteners must be identified and treated as a distinct subset.** Manufacturers are required to identify critical structural fasteners and critical bonding fasteners so that specification, tightening, and inspection expectations are anchored to the joints that govern structural capacity and electrical bonding continuity.

- Critical fasteners must be specified.** For each critical fastener, manufacturers must document key attributes, including geometry and fit, tolerances, coatings/plating, materials/alloys, and strength-related properties (e.g., proof/yield/tensile). This will be accomplished through recognized consensus standards (ASTM/ISO/SAE/ASME, etc.) or through a documented quality management system that controls those properties (see Figure 8)
- Installation instructions must be complete for critical joints.** For critical fasteners, installation manuals must go beyond a torque value and must include the assembly details needed to achieve a known, controlled pretension. Critical fastener details (material properties, coatings, geometry) must also be defined when the mounting system manufacturer does not supply the fasteners. The intent is to reduce “installer interpretation” on the joints that will carry the most consequence.



Figure 8: Examples of hex cap screws that contain markings which designate the manufacturer and screw mechanical properties according to a consensus standard.

4.1.2. New Optional Requirements

The revision also provides options for manufacturers, allowing them to reduce uncertainty in torque-to-tension outcomes or deploy fastening systems that do not rely on torque as the primary control variable.

- Experimentally based minimum clamp-load determination (statistical minimum).** Manufacturers may establish a minimum expected clamp load for a representative joint using test data generated with the same assembly process and tools specified in their installation instructions. Results are statistically analyzed to set a conservative minimum clamp with defined confidence, and that value can then be used to demonstrate the required safety margins.
- Support for other fastening systems and non-torque tightening methods.** The revision provides manufacturers with a pathway to use fastening systems that do not rely on torque-controlled tightening to achieve the desired clamp load and are designed to reduce variability or simplify quality control (e.g., lockbolt-type hardware, tension-controlled fasteners). These systems may be used for critical joints, provided the manufacturer demonstrates the minimum clamp load and provides field instructions that make the test outcome reproducible (tooling, settings, and tightening method).

These mandatory and optional requirements begin to address several of the gaps identified earlier in this report.

- Tightening method (torque control):** The optional experimental clamp-load method, defined in this revision of the standard, establishes a minimum clamp load that reflects real assembly variability. The revision also makes it clear that mounting system manufacturers may use alternative fastener systems that do not rely on torque-

controlled tightening.

- **Fasteners:** The revision closes a major documentation gap by requiring complete specification of critical fastener properties. It does not create a unified industry standard for all “alternative structural bolted joints,” but it does provide a pathway to qualify certain alternative fastening systems when manufacturers are willing to demonstrate clamp-load performance and provide repeatable field procedures in the future. Field issues such as storage, handling, and cleanliness can be addressed through installation requirements, but enforcement will ultimately depend on contractor practices and project QA/QC.

The June 2025 revision of ANSI/UL 2703 is a meaningful step forward. It raises baseline expectations by requiring clearer identification and specification of the critical fasteners. It introduces practical measures to reduce pretension uncertainty that manufacturers may adopt. It also creates a path for qualifying fastening systems that do not rely on torque to be tightened.

4.2 Adoption of Practices defined in the forthcoming ASCE Manual of Practice

The ASCE/SEI Solar PV Structures Manual of Practice (MOP) will be a new consensus-based document that provides rational design guidance for reliable photovoltaic mounting structures. Developed under the direction of the ASCE/SEI Solar PV Structures Committee, the manual is expected to be released in late Q1 2026. Although it will not carry the force of an ASCE standard, the MOP is intended to capture best practices in a rapidly evolving field and to serve as a pre-standard precursor that can be refined through the ASCE consensus process and, over time, inform future engineering standards.

Among the topics covered in the MOP, bolted joints are especially relevant to this report. The manual underscores that joint reliability hinges on achieving controlled pretension through consistent installation practices—a point that aligns directly with the gaps identified earlier in tightening methods, tool selection, and fastener performance. In the near term, mounting structure manufacturers could begin addressing several of these gaps by incorporating this guidance, in whole or in part, into their installation requirements and quality processes.

The MOP groups PV mounting structure bolted joints into two broad categories: traditional and alternative structural bolted joints. This framework ties PV practice to established structural bolting concepts while still accommodating the wide range of PV-specific joint types used in mounting structures.

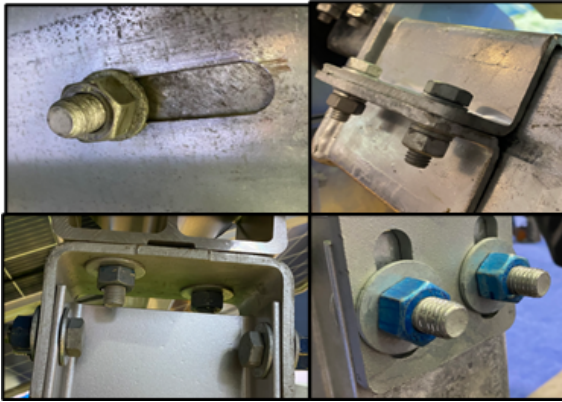


Figure 9: Saddle-bracket to pile, and inter-rack joints (1/2 inch and larger bolts) are categorized as traditional structural joints under the MOP.

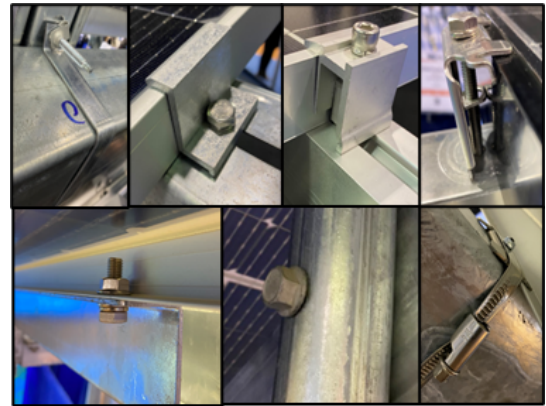


Figure 10: Module-through bolted joints, top-down clamp joints, and torque tube joints (less than 1/2" bolts) are categorized as alternative structural joints under the MOP.

Traditional Structural Joints: Bolted joints using standard high-strength structural bolt sizes (1/2-inch and larger) are classified as traditional structural joints (connections). These joints are commonly used for saddle-bracket-to-pile and for inter-rack joints (see Figure 9).

The MOP will require tightening methods and fastener specifications for traditional structural bolted joints to comply with the RCSC Specification (RCSC, 2020).

- Tightening Methods & Tools:** The RCSC Specification is clear that the objective of tightening is pretension, not torque. It treats the fastener assembly, installation method, and tightening tool as a single system that must consistently deliver the required minimum pretension level. When torque wrenches are used, the Specification requires regular verification of torque settings to ensure the specified minimum pretension is consistently achieved, accounting for changes in fastener lots, lubrication, and other friction-related variables. Most importantly, the Specification explicitly allows fasteners that do not use torque wrenches for tightening, such as tension-control bolt assemblies and direct-tension washers (DTI washers) (see Figure 11). One variation of the DTI washer contains silicone indicators that squeeze out when the washer is fully compressed, giving installers an immediate visual cue that the bolt has reached the minimum pretension.



Figure 11: DTI washer with silicone indicators provides a visual clue that the minimum pretension has been achieved during tightening.

- Fasteners:** The RCSC Specification identifies the ASTM standards that define the required geometry, materials, strength, and coating characteristics for bolt, nut, and washer assemblies used in traditional structural bolted joints. The Specification also

sets clear expectations for storage, cleanliness, lubrication condition, and component matching to maintain consistent friction conditions during tightening. Lastly, the Specification also limits the reuse of coated or galvanized bolts and nuts, as reuse can alter the achieved pretension, even when the same tightening method is used.

Alternative Structural Joints: The MOP groups joints that use nonstandard structural bolts ($\frac{1}{2}$ inch and smaller) and materials as alternative structural joints. Many joints in PV mounting structures fall into this category, including module-through bolted joints, top-down clamp joints, and torque-tube joints (see Figure 10).

Although the RCSC Specification does not apply to alternative structural joints, the MOP emphasizes that these joints must still be rationally designed by the Engineer of Record or the mounting-system designer. That responsibility includes establishing how the joint will be assembled in the field and ensuring that the selected tightening method can consistently deliver a known, controlled pretension.

- **Tightening Methods & Tools:** The design process begins with defining assembly procedures and selecting a tightening method that consistently delivers a known, controlled pretension in the field. Accordingly, the MOP requires that minimum pretension, rather than torque, be specified in structural drawings and installation manuals.

The MOP recognizes alternative fastening technologies, such as lockbolt-type systems that provide better pretension control than torque-controlled tightening. Although torque-controlled tightening is still allowed, it is only if daily verification of the tightening torque is completed using representative fasteners in a tension calibrator that variables such as lot variation, lubrication, handling, and surface condition are taken into account.

The MOP's guidance on tooling follows the same principle. Rather than prescribing specific tools, it defines the control concept: any tool or system used must be capable of delivering pretension within a controlled range at PV scale in field conditions.

- **Fasteners:** The MOP further requires the EOR (or mounting structure designer) to rationally design the connection, including the fasteners, using design strengths supported by individual fastener tests, full-scale joint testing, or future consensus documents tailored to PV structural joints. To support this, the MOP encourages designers to specify fastener properties critical to fastener performance using established engineering standards and to treat the bolt, nut, and washer as a matched assembly rather than as interchangeable 'commodity' parts.

4.3 Filling Industry-Wide Knowledge Gaps on Bolted Joint Installation

Torque control tightening is currently the established, default method for assembling PV mounting structure bolted joints. Unfortunately, small differences in installation conditions can

result in significant variations in the pretension achieved in the field, despite the best efforts of EPCs, contractors, and inspectors. There is a clear opportunity to improve consistency by providing targeted education that aligns design assumptions, installation practices, and inspection checks with the fundamentals that govern pretension.

The training opportunities summarized here are intentionally high-level. Developing a full curriculum, a detailed list of lesson topics, or role-specific course outlines is outside the scope of this report. The aim is to identify the most important concepts that education providers can translate into learning objectives, short modules, practical assessments, and field-ready job aids.

Training for EORs, designers, and mounting structure manufacturers

- **Control of pretension is critical to bolted joint reliability:** Reinforce the idea that bolted joint capacity depends on pretension, and that the selected tightening method directly affects pretension scatter, which must be considered in design assumptions and acceptance criteria.
- **Limitations of torque-control tightening:** Torque control is widely used and often viewed as a straightforward, low-cost tightening method. Unfortunately, the method often results in a wide scatter in pretension, driven mainly by friction in the threads and beneath the turning element. In the field, the clamp load achieved can differ markedly from calculated values due to differences in installation technique, fastener condition and cleanliness, coating characteristics, and the accuracy of the tightening tools themselves. Delivering consistent pretension with torque control ultimately requires investment in higher-quality tools and deliberate management of fastener friction, costs that are frequently overlooked.
- **Awareness of alternative tightening methods:** Recognize that there are established tightening methods (and fasteners), particularly for ½-inch and larger bolts that are less affected by friction and provide a visual indication that at least a minimum pretension was achieved (e.g., tension-control bolts or direct-tension-indicator approaches).
- **Specifying a complete tightening method:** Contractors and inspectors would benefit from clearer descriptions of the tightening process, including the intended pretension. Specifying the tightening method in detail is critical, including tightening sequence, snugging approach, re-torque guidance (if any), and whether lubrication or anti-seize is allowed/required.
- **Verification expectations and change control:** Set realistic, auditable verification requirements (inspection points, sampling, documentation), and define how substitutions, fastener-lot changes, or field-driven deviations are evaluated and approved.

Training for EPCs and Contractors

- **Dealing with gaps in installation manuals:** Recognize that PV module and mounting system manuals may not include the installation and tightening details needed to achieve the target pretension. Crews need a way to identify missing information and escalate questions before installation turns into rework.

- **Important nuances of torque-control tightening:** Torque is simply the method used to generate bolt pretension, not the objective itself. When torque-control tightening is specified, achieving a predictable pretension depends on managing both the applied torque and fastener friction. Controlling friction is just as critical as torque control, and it is affected by thread cleanliness, corrosion, debris, moisture, coating damage, galling, and inconsistent lubrication or anti-seize practices.
- **Tool selection and maintenance tied to joint criticality:** Choose tools and procedures based on how sensitive the joint is to pretension variability (and what the torque tolerance implies) and maintain calibration and torque verification practices that survive real site conditions.
- **Documentation and nonconformance response:** Standardize what gets recorded (fastener lots, lubrication practice, tool calibration, verification checks) and how assembly issues are handled (cross-threading, damaged fasteners, substitutions, “felt tight” joints that don’t meet acceptance criteria).

Training for Inspectors and Owner QA/QC

- **What inspection can and cannot prove:** Clarify the limits of torque checks and torque marks as indicators of pretension, and why a “pass” torque reading doesn’t necessarily confirm the required pretension was achieved during tightening.
- **Confirming the required configuration is actually defined:** Verify that the project documents identify critical joints, approved fasteners, any lubrication rules, required tools/method, and acceptance criteria, especially where manuals are silent or ambiguous.
- **Field observation and sampling practices:** focus inspection on observable indicators that correlate to quality (joint fit-up, washer placement, alignment, thread engagement, signs of galling/corrosion, tool usage discipline), supported by an explicit sampling plan.
- **Records review and traceability:** Require evidence connecting installation to controls, such as calibration certificates, audit logs (when used), lot traceability, and documented dispositions for deviations.
- **Escalation and disposition pathways:** define when repeated deviations trigger broader corrective action (method change, retraining, increased sampling, supplier investigation), rather than treating each issue as an isolated punch-list item.

Organizations with training capabilities, like NABCEP, SEIA, and ASCE/NCSEA could turn this list of training concepts into short, role-specific training modules with clear learning objectives. The modules could include practical checks and job aids, such as installation checklists, friction/condition “red flag” guides, and inspection sampling templates. Packaging these training modules as CEU-eligible courses would also make it easier for employers to qualify crews and for owners to specify minimum expectations for joints critical to the structure or bonding.

4.4 Tool Selection – Moving Beyond Torque Specification Only

When a critical solar PV bolted joint is tightened under torque control, the tightening torque

alone often does not provide sufficient information to consistently achieve the target pretension. The same torque can produce very different clamp loads depending on how the tool reacts to joint stiffness. Some joints behave “hard,” with a stiff stack-up and quick seating; others are “soft,” with thin or compressible layers; and some are slightly misaligned because of terrain or construction tolerances. In practice, these differences can lead to inconsistent results. Leaving tool selection entirely to the contractor, who is forced to use trial and error to find the right tool, does not always result in the pretension required.

A recurring theme in discussions with contractors and tool distributors is that installation manuals should move beyond listing a torque value and instead describe the tool type, expected capabilities, and appropriate settings for each critical joint. This does not require naming a specific brand or model. It simply means narrowing the acceptable tool types and configurations based on controlled, realistic field testing. Manufacturers would also benefit from working with tool distributors who regularly support utility-scale PV construction and understand which tools perform reliably in harsh site conditions.

For each critical joint, the manual could identify:

- Preferred tool type
- Acceptable alternatives (if any)
- Limited-use tools (for example, tools that may be used for rundown/snugging only)
- Required accessories or constraints driven by the joint (for example, right-angle access, reaction approach, or adapter limitations)

Note: Installation manuals should also be explicit about the role of impact drivers. They are common on PV sites because they are fast and rugged, but they are not well-suited to delivering controlled torque. If impact tools are used during installation, the manufacturer should define where they are acceptable and what limits apply, rather than leaving that decision to the contractor.

The installation manual could also describe the tool's capabilities, for example.

- Target tightening torque capability tolerance, expressed as a percentage of the mean value. Example: Target torque = \bar{T} (mean) and tolerance expressed as a percentage of \bar{T}
- Proposed run-down and tightening speeds.
- If appropriate, angle limits for the joints.
- Propose data logging capabilities.

The installation manual could also provide clear guidance on adapters and access tooling, such as extensions, universals, crowfoots, and specialty sockets, as well as configuration limits when adapters are unavoidable. It should likewise establish a simple rework rule for disturbed joints, so crews know exactly what to do when a fastener is loosened, replaced, or reseated, rather than improvising different practices in the field.

Clearer, field-validated guidance on tightening tools and installation methods developed with

input from tool distributors who understand PV site conditions would benefit both manufacturers and contractors and lead to more uniform pretension and more reliable joints.

5. Future Innovations

The immediate improvement strategies outlined in the previous section focus on making the best use of existing methods, tools, and new and improved standards and guidance. They offer a practical way to tighten up current practices and reduce pretension variability in the field, especially at critical joints. But even with clearer specifications, better training, and more deliberate tool selection, fundamental limitations remain. Torque-based tightening will always be affected by friction, tool performance, field conditions, and assembler errors. Joint quality will continue to vary unless better control mechanisms are built in from the start.

Looking ahead, further progress will depend on technological innovation, not just in how threaded fasteners are tightened, but in the design of the tools and fasteners themselves. The sections that follow explore two key areas where future development could significantly improve joint reliability and field performance: tightening-tool technology and threaded-fastener design. These innovations have the potential to reduce the industry's dependence on torque audits, minimize pretension uncertainty, and make quality control more automatic and robust at utility-scale PV construction sites.

5.1 Tool Technology

5.1.1. Development of Ruggedized Precision Tightening Tools for Solar PV Sites

As the utility-scale PV industry considers a shift toward more precise and repeatable tightening tools, tool reliability and maintenance are practical barriers.

A small but growing number of tool manufacturers have developed and are marketing field-oriented precision tightening tools specifically for utility-scale solar workflows, including controlled impact wrenches and nut runners. These tools are relatively new to the solar PV industry, and there is limited publicly available information on their long-term reliability. But early anecdotal feedback is positive, and this early market activity signals interest in more controlled fastening approaches (Fisher, 2024) (Atlas Copco, 2026).

Utility-scale solar jobsites are harsh enough that many precision tightening tools, originally designed for controlled, indoor manufacturing environments, do not perform reliably over long construction cycles at PV sites without added protection, verification, and support. The gap between how these tools are designed and the realities of PV construction is significant: heat, dust, drops, rain, and wide temperature swings all accelerate wear and calibration drift. Before precision tightening tools can be widely adopted in the solar PV industry, they must operate reliably at PV sites with minimal care. In this context, ruggedization centers on two essential attributes:

Field Durability: Tools deployed on PV sites should be engineered to withstand harsh physical conditions, including frequent drops, extreme temperatures, and constant exposure to dust, grit, and moisture. A practical starting point is to define tool (enclosure) protection using the Ingress Protection (IP) framework IEC 60529 (IEC, 2013). An IP65 rating or higher is generally

considered the minimum for tools under this rating system. Durability can also be benchmarked using IEC 60068-2 series methods (e.g., vibration, shock, thermal cycling) appropriate to the expected duty cycle and handling loads (IEC, 2025).

Serviceability: Even the most robust tools require maintenance in the field. Ruggedized design must therefore prioritize ease of service, including modular components that can be quickly replaced, such as sensors, and practical on-site calibration or verification methods. Long-term success also depends on the availability of spare parts and diagnostic support to keep tools operational at remote PV sites.

The industry is at an inflection point. For precision tools to gain traction in utility-scale PV construction, they must deliver not only reliability and accuracy but also survive job-site conditions without extraordinary care. That will require continued advances in tool design, performance testing at solar construction sites, and improved field support. Until then, the widespread deployment of non-ruggedized precision tools is a risky decision, and contractors will likely continue to rely on simpler, more durable tools that, while less precise, can withstand the job.

5.1.2. Adoption of Advanced Smart Tool Technology

As the utility-scale PV industry recognizes the limitations of torque-controlled tightening with conventional tools, smart tools offer a practical way to improve installation quality. These tools guide installers during tightening and verify each joint as it is completed, shifting quality control from post-installation inspection to real-time assurance. Although this technology is common in high-volume manufacturing, applying it to PV construction introduces new considerations. Smart tools provide immediate feedback on torque and angle, helping crews achieve correct tightening on the first pass. Basic models use simple visual or audio cues and store tightening records on the device. More advanced versions can connect to mobile apps or cloud dashboards, allowing supervisors to review tool performance and generate reports. Each tightening action becomes traceable, linking the event to the joint location, tool ID, installer, and timestamp.

Why This Technology Matters for Utility-Scale PV

Large PV projects contain millions of bolted joints, many of which cannot be accessed once modules are installed. Rework is costly and often disruptive. Missed fasteners, inconsistent torque, and human error may not be detected until inspections, commissioning, or later in the mounting system's life. Smart tools reduce this risk by guiding installers, confirming that joints are tightened correctly, and recording the data needed for verification. Not every joint requires this level of control, but buried or hard-to-reach connections stand to benefit the most.

Recent field experience from a major EPC firm shows that smart nut runners can perform well on large PV sites. In that case, the contractor used a cordless nut runner with an integrated controller to manage a high volume of structural joints. The tool delivered consistent tightening accuracy and remained reliable in mud, dust, rain, and direct sun. Project staff also noted that the tool's verification features and digital records improved installation quality and made it easier to demonstrate compliance. This early use suggests that smart tools designed for outdoor construction can meet the demands of utility-scale PV work (Atlas Copco, 2026).

Evolving Capabilities and the Role of Data

Smart tightening tools are beginning to support broader data capture. Some PV projects are testing RFID tags on structural components and modules, allowing tools to scan the tag and link each tightening record to a specific location. Other tools are being developed with integrated GPS or ultra-wideband positioning for even finer tracking. When combined with onboard sensors, these systems could automatically log torque, angle, fastener type, timestamp, and geographic position, creating a detailed audit map of the site.

This level of traceability supports a shift toward data-driven quality control. Bill Poulin, Managing Partner and Co-founder of Eclipse-M and a contributor to this report, notes that torque alone does not guarantee joint integrity: “Does that tell you the torque is right? Not necessarily, but you can correlate those things and say there’s a high probability that the torque is right.” This perspective frames joint quality as a matter of statistical confidence rather than a single measurement. By capturing torque, angle, and usage trends together, crews can detect drift in tool performance and intervene before errors spread.

As Poulin explains: “I’m going to get dramatically and demonstrably better results because I can track torque, see the drift in performance, and stop guns from working.” This type of feedback loop moves QA from reactive checks to preventive control. Smart tool data also provides downstream protection. Installers value having a clear record of what was tightened, when it was done, and how it performed.

As Poulin notes: “The folks doing this work love the idea of having a data trail... then they can prove, ‘Here’s what I did, and it’s all in range. And where it wasn’t, we went back and addressed it.’” While crews can achieve good results with manual methods, doing so requires time, careful oversight, and repeated checks. Smart tools offer a way to reach the same level of confidence with less rework and greater consistency.

Barriers to Adoption

Despite their potential, several challenges limit the broader use of smart tools in PV construction. Many tools are designed for clean, controlled manufacturing environments rather than utility-scale solar PV sites. Limited connectivity can also slow data transfer; without reliable cell or Wi-Fi service, tightening records may remain on the tool until they are manually downloaded.

Demand is another barrier. System owners benefit most from improved documentation and reduced long-term risk, but EPCs and contractors typically bear the cost of the tools. Without clear incentives or contractual requirements for traceability, adoption remains low. This limited demand reduces the likelihood that tool manufacturers will invest in rugged, solar-specific designs.

Path Forward for Implementation

A practical approach is to begin with critical or high-risk joints, especially those that become inaccessible after installation. Project teams can define the tightening data needed, such as torque, angle, timestamp, and tool ID, and pilot smart tools capable of capturing it under real field conditions. Success can be measured through reduced rework, fewer audit failures, and

more consistent results.

Broader adoption will require alignment across stakeholders. PV site owners can drive demand by specifying traceability requirements. EPCs and contractors can benefit from improved QA and faster commissioning. Tool manufacturers are more likely to invest in solar-specific solutions when they see clear market signals.

Long-term success will also depend on integrating tool support into daily field operations. This includes calibration procedures, spare tool inventory, training, and simple data workflows that keep smart tools reliable throughout the project. As the PV sector continues to scale, tightening tools that can verify, not just apply, torque may play an important role in improving installation quality and long-term reliability.

5.2 Fastener Technology

5.2.1. Development of Load-Indicating Washers for Alternative Structural Joint Fastener Sizes

Direct-tension-indicating (DTI) washers are widely used in traditional structural bolted joints to confirm that the required pretension has been achieved during tightening. When these washers are used, torque control is no longer the primary means of ensuring pretension; the installer tightens the bolt or nut until the washer's indicator shows that the minimum load has been reached.

Most DTI washers rely on small protrusions or dimples that compress under load. As the joint is tightened, the gap between the dimples reduces or disappears, providing a straightforward, reliable signal that the bolt has reached the proper pretension.

A variation of this design incorporates silicone indicators that extrude when the washer is fully compressed. The expressed silicone gives installers an immediate visual cue that the minimum pretension has been met (see Figure 11). This style is particularly appealing for PV mounting systems and module-attachment joints, where a simple, unambiguous indicator would be valuable.

DTI washers are currently available only for structural bolts $\frac{1}{2}$ inch in diameter or larger. While they could be used in traditional structural joints in the mounting structures, they do not exist for alternative structural joints (less than $\frac{1}{2}$ "). This gap represents a significant opportunity for washer manufacturers to develop products tailored to the needs of the solar PV industry.

5.2.2. Adoption of Belleville Washers

Belleville washers can also provide a visual indication that a bolt has been tightened to minimum pretension. When the joint is unloaded, the washer maintains its conical shape, but as the bolt is tightened and the pretension increases, the washer gradually flattens. Once it is fully compressed and resembles a standard flat washer, the joint has reached the target pretension (see Image 12). In practice, the installer would tighten the bolt or nut until the washer goes flat.

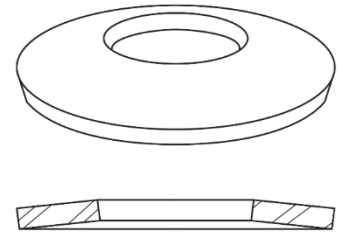


Figure 12: The Belleville washer shown here can provide a visual indication that a bolt has been tightened to the minimum pretension.

While Belleville washers are not as precise as direct-tension-indicating (DTI) washers, they still provide the assembler a simple visual cue that the joint has reached a minimum level of pretension.

Unlike DTIs, which are currently limited to ½-inch structural bolts, Belleville washers are available in a wide range of sizes, including those commonly used in alternative structural joints in PV mounting structures. Because these washers are already commoditized, they can be incorporated into alternative structural joints with minimal lead time and at relatively low cost.

Adopting these washers will mainly require mounting structure manufacturers to procure and test the optimized washer, revise their installation manuals, and provide hands-on training for the assembler. With that in place, Belleville washers could offer a quick, practical improvement in clamp-load consistency for the smaller joints.

Caution: Both Pretension-Indicating washers and Belleville washers provide a visual indication that the minimum pretension value was achieved. They do not indicate if the pretension is too high. Such washers should be developed or adopted with caution if used in alternative structural bolted joints where

5.2.3. Standardization of Lock Bolts and Tooling

A lock bolt has circumferential grooves or serrations along its length. During installation, the lock bolt and collar are assembled manually. An installation tool grips the pin, pulls it to the required pretension, and then swages a collar onto it to hold it in that elongated state. This process achieves a predictable, accurate pretension without relying on torque or being affected by friction variations.

Lock bolts are commonly used in Europe to secure critical joints in structural bolting applications and are approved for use in steel construction under Eurocode 3. They are routinely deployed in bridges, wind turbine towers, cranes, and other vibration-intensive structures.

Despite their established use in structural applications, only a few mounting-system manufacturers have adopted lock bolts, largely due to concerns about tool maintenance and overall cost. Installation tools are known to require frequent maintenance in solar PV construction environments, where sand and dirt accelerate wear. These challenges, combined with the higher cost of lock bolt hardware, have limited broader adoption in an industry that installs millions of fasteners on large projects.

Cost pressures are a recurring concern. “If you were to take a racking system that is currently being bolted, and now you’ve thrown a lock bolt on that, you’ve increased the cost,” says Mike Madden. “...so, you’re going to get pushback from installers and site developers when dealing with potentially millions of fasteners.”

In the long term, broader adoption of lock bolts in the solar PV industry will require a focused effort to address these barriers. Tooling must be developed that can withstand the sand, dirt, and abrasive conditions typical of most PV construction sites. At the same time, the industry will need to move toward greater standardization of lock bolt hardware and installation tools, while safeguarding existing intellectual property. If these steps are taken, a larger supply base could emerge, ultimately lowering both hardware and tooling costs.

5.2.4. Module Retention Devices

Spring-loaded module-retention devices, such as clips and wedges, provide an alternative, low-cost method for securing PV modules to mounting structures without threaded fasteners or pretensioned joints. These devices create a positive mechanical connection between the module frame and the mounting structure through serrated teeth or other engineered engagement features. Field installation is straightforward and repeatable, typically requiring only simple hand tools such as mallets or purpose-built pliers.

The technology simplifies module-retention practices, reduces component count, and supports consistent installation quality. Their simple installation also makes them well-suited for automated module assembly in the field, particularly if module frames, retention devices, and mounting-structure interfaces are designed as an integrated system. Such integration would require collaborative product development between module manufacturers, mounting-structure manufacturers, and retention-device suppliers.

Despite these advantages, there is currently no published, independent research evaluating the long-term reliability of these devices across diverse environmental and loading conditions. In addition, performance standards addressing the durability of these connections under dynamic wind loading and in corrosive environments have not yet been established.

With closer coordination among manufacturers and a research base supporting aligned standards, the industry may find that spring-loaded retention devices offer the simplest and most cost-effective method for future module attachment.

6. Conclusion

Utility-scale PV mounting structures collectively contain millions of bolted joints, many of which are critical to structural reliability and electrical bonding. Despite this, industry practice continues to rely on applied torque as the primary control variable, an approach that is both easy to deploy and inherently flawed. In real-world conditions, torque is a poor predictor of the clamp load that ultimately governs joint capacity. Variations in friction, contamination, joint configuration, and tool performance all contribute to scatter in pretension, making it difficult to ensure joint reliability at scale.

Torque-control tightening will remain the dominant method in the near term, but significant improvements can still be made by improving how torque is specified and applied. The June 2025 revision to UL 2703 offers a practical path forward, requiring mounting structure manufacturers to identify critical structural and bonding fasteners, fully specify their properties, and provide installation instructions that go beyond torque values to include the procedures and tooling needed to achieve repeatable pretension.

The forthcoming ASCE/SEI Solar PV Structures Manual of Practice builds on this by aligning PV joint design with rational engineering expectations and treating the fastener, tightening method, and tool as an integrated system. Whether for traditional or alternative joints, achieving consistent pretension requires clear documentation, field-ready guidance, and methods that account for the realities of PV construction.

Tool selection for critical joints cannot be treated as a contractor's decision. Manufacturers should define acceptable tool types, target tolerances, rework protocols, and any joint-specific constraints. These decisions must be informed by field testing and developed in collaboration with tool suppliers who understand the demands of utility-scale PV environments.

Looking ahead, emerging technologies, such as smart tools, ruggedized precision equipment, direct-tension-indicating washers, lockbolts, and module retention devices, offer promising paths to reduce variability and embed quality into the tightening process. However, adoption will depend on the practical implementation, standardization, and alignment of costs and responsibilities across the value chain.

At its core, this report identifies a shift in mindset: torque is not the outcome, pretension is! The tools, standards, and frameworks now exist to close the gap between design intent and field execution. What remains is for industry to act, starting with the joints that matter most.

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