Splice Body and Termination Playbook

cleanpower.org

AMERICAN CLEAN POWER

Table of Contents

AMERICAN CLEAN POWER

1 Introduction

The renewable energy industry has been the electrical industry's largest single user of 35kV cables over the last two decades. While each cable requires multiple accessories (terminations or connectors) often due to cable length, installation utilizing directional boring, or for various other installation reasons, the use of splices may be required. Many of the terminators and connectors that are on the market were originally marketed to the utility industry and may not be best suited for renewable facilities. Further, as renewable energy facilities have gotten larger, the corresponding lengths of cables have gotten longer, and the usage of splices has increased.

Splices, like the cables they are utilized with, are engineered to last as long as the cables. While many aspects of the power cables used in the renewable energy field appear to be identical to those of the industrial or utility electric industries, the operating parameters are not the same. Over the last decade or more, a rise in accessory failures on wind and solar farms has been documented, indicating that despite the engineering design, they are prematurely failing. Yet, at the same time, utility applications were not seeing the same increase in failures. Many of the manufacturers have instigated studies to determine why.

Any failure of the collector system is expensive. As variable generation facilities are not on demand power plants, but are as available power plants, the cost of an outage can vary widely. Making a predication for the true cost of a failure is very difficult, primarily as there is no way to determine precisely if an outage will be followed by high resource days or low resource days, or whether that outage will affect a few megawatts, or hundreds of megawatts.

With PPA prices as variable as the generation itself, putting a single fixed cost on a cable fault, for the fleet, is not possible. Even within a single owner's fleet of facilities, the loss costs for one facility or cable may not be related at all to the loss costs for another facility or another cable. Those owners who have experienced significant outages have already determined their costs of losses, at least for that facility that suffered the failure. For those owners that haven't experienced a catastrophic failure, we offer an average daily lost revenue range of $40,000 to $200,000 as a starting point for evaluation (not including repair costs). As the size of renewable generation facilities and renewable collector circuit sizes increase, revenue losses from a single, unexpected, outage can also be expected to increase.

With some splices being twice as expensive (or more) than others, and some power plants having hundreds of splices installed, it's up to the reader to calculate their own costs and risks. Although the economics must be calculated by the user, the manufacturers studies as to why failures have occurred are integral to the analysis of risk.

2 Types of Accessories & Couplings

Accessories that connect a cable to a different device are called connectors.

Accessories that connect one section of cable to another section of cable are called couplings, or splices. With medium voltage (MV) cable, to install a splice requires removing the different portions of the cable jacket, insulation, and electrical stress control portions, down to the bare conductor. The two pieces of conducting cable are then connected with a coupling. Once the conductor is coupled, the electrical stress control, the actual MV insulation, the shielding and outer jacket must be recreated. The complete finished splice is usually buried underground, and its location marked in case of future need to locate.

2.1 Compression Couplings & Connectors

Perhaps the oldest, and possibly the most common conductor splicing method is a compression coupling. Compression couplings and connectors have been shown to work well for common utility applications.

Compression connectors use a hydraulic or mechanical crimper that has dies matched to a specific cable and termination size to compress the ferrule (the hollow tube to which the cable will be inserted) onto the electrical conductor. The connector itself is usually a one-piece construction. Flattened at one end, with holes formed to allow it to be bolted to a matching terminal, it is a round open tube at the other end which may be filled with anti-oxidation grease. The electrician is supposed to prepare the cable, and the prepared end of the cable is then fitted into the termination. The hydraulic or mechanical press is a specialized tool, with preset, precalculated pressures. When applied, the terminal is "compressed" into the conductor. The dies used with the press must be from that specific tool manufacturer and must precisely match the wire/terminal combination being used. Failure to use the proper die, pressures, or even the proper termination will result in a poor electrical connection, high resistance, and premature failure.

The cost of compression connectors is relatively low, but in renewable usage, their failures are documented as relatively high. The extremely variable loading of renewables (regularly between 0% and 100%) and the usually "average" continuous loading of utility cables appears to be a critical factor in this difference. Compression connections and couplings required specialized compression tools and have consistently been shown to have inferior performance in renewable applications.

2.2 Shear Bolt Couplings & Connectors

Shear bolt couplings and connectors perform the same exact function as compression couplings and connectors. They do not require specialized tools, hydraulic presses, dies, or jigs to install.

Threaded bolts with fixed, engineered shear points provide consistently even compression forces. Typically, they have much greater mass than any compression connectors and couplings, meaning that it better conducts heat away from the connection. Since the couplings themselves do not deform, they can be made with more material, providing more thermal mass, which will remain cooler. No deformation also means that they have a nearly perfect alignment and fit with the insulating bodies. Most shear bolt designs are similar in mass, so thermal conductivity is normally comparable between brands. The same amount of heat applied to a shear bolt connection will have a lower temperature and lower expansion than will a comparable compression connection.

Figure 1 (left) One style of shear bolt coupling with hex head bolts, operated by a typical socket set. Fig 1 (Right) Another manufacturers shear bolt coupling with Allen head bolts. Connectors would have a bolt connection pad on one end. With either type, the shaft of the bolt will shear when the proper torque is reached

The shear bolt connector is specifically engineered with pre-inserted threaded bolts protruding from the ferrule (or body) which compress against the conductor once it has been inserted into the shear bolt body. The bolts are tightened with a common socket wrench or Allen wrench. Unlike other electrical bolted connections, a torque wrench is not usually required, nor recommended. The shear bolt itself tells us when it's been properly tightened; the shear bolts tighten until they reach a precise, engineered, break point at which point the bolt itself "shears off" removing both the ability to apply "extra" pressure and, just as with compression connections, the termination can no longer be removed.

While it is virtually impossible to make sure that every electrician performs their tasks perfectly, in laboratory testing by multiple manufacturers, it has been shown that shear bolt couplings are vastly superior to compression couplings in resisting the effects of improperly prepared conductors. Though the cost of shear bolt connectors is comparatively high, in renewable usage, their failures are documented as relatively low.

The reason for this discrepancy seems to be the load cycles that renewables have, and that utilities do not. Whereas renewables commonly, and regularly, go from full load to zero, (in solar, every day), utilities do not. This full load to zero leads to very hot and very cold cables. Utilities typically have a mid-range load and almost never go to full load or zero load, so they never get "cold" and never get "really hot". The heat input at "full load" is 400% the heat input at half-load.

Greater mass and size in shear bolt connectors mean more thermal capacity, more conductor contact, lower resistance, and terminations that remain much cooler with the same heat input.

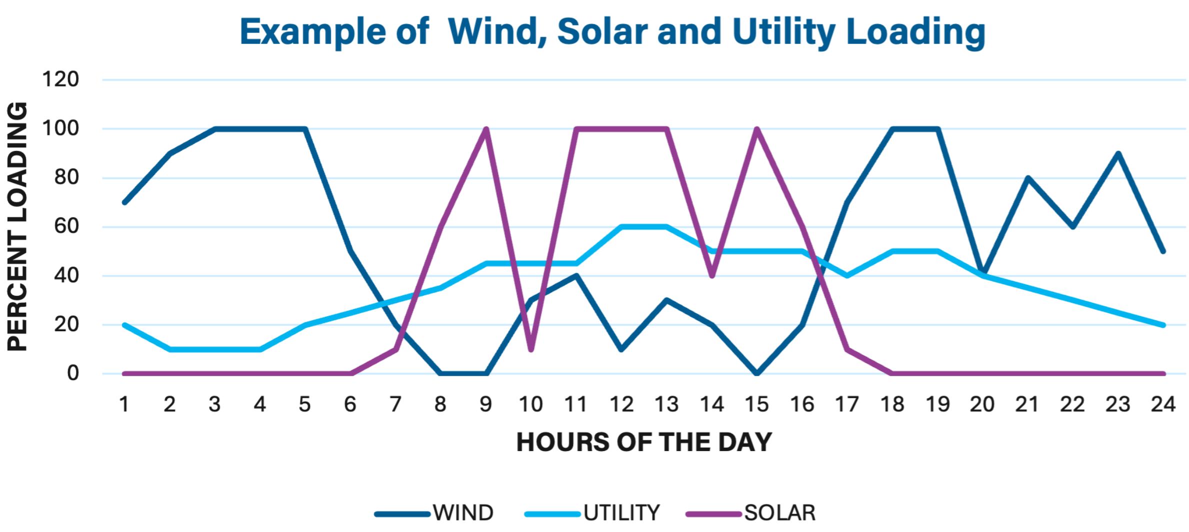

Figure 2: A 24-hour load cycle example for cables in wind generation, solar generation, and utility usages. Utility cables seldom get really "hot" or "cold"; renewable cables regularly get really "hot" and really "cold."

3 Failure Analysis

Many accessory manufacturers have investigated the lower performance of splices when utilized in renewable energy facilities. Many have come up with similar causes of the high failure rates as compared with utilities.

3.1 Partial Discharge

Overall, it has long been documented that the failure of the actual cable, termination, T-body, splice, or stress cone is primarily through partial discharge. Any cause of partial discharge in a termination is therefore driving that termination to failure.

3.2 Compression & Shear Bolt Connectors

Compression connectors have often been found to have been mis-matched with the compression tool. Whether it is the wrong size die for the wire, the wrong manufacturers die for the tool, the wrong size terminal, the wrong compression strength – all have been verified as causes of partial discharge or excessive heat generation. Improperly sized and improperly matched tools results in improper compression strength.

Compression connectors are easy to create a "pinch" of material which will then create a discharge point and lead to failure. Both compression lugs and shear bolts can be dressed to smooth out such discharge points.

Figure 3 Example of a compression connector with a slight "banana" shape but, more importantly, showing a sharp tab left from the compression tools. This tab will become a point of Partial Discharge within the insulating body and can lead to failures.

Shear bolt connectors, with their non-deformation design, provide a much more precise fit inside the insulation materials. Compression connections require multiple compressions and, if they are not performed precisely, can deform the ferrule into a "banana" shape which may leave voids inside the insulation materials after installation.

Shear bolt connectors, when the bolt shears off, may leave high spots, or burrs, on the remaining bolt surface, both of which can cause damage to the accessory and partial discharge. These high spots must be detected and smoothed by the installer.

A possible drawback to shear bolts is that when the bolt breaks, it can leave a sharp tab, or point, protruding from the sheared bolt. Like the tab in Figure 3 for a compression-style connector, this sharp point will create partial discharge. During failure dissections and root cause analysis of failed terminations, it has been seen that virtually all shearing methods can suffer from this remnant sharp edge, and this seems to have been a common failure mode for many shear bolt failures.

3.3 Service Conditions

Medium voltage cables, in renewables, do not have the same service conditions that utilities experience. The cable and accessory manufacturers are the same, but failure rates are greatly different.

3.4 Loading

Utilities have cables that are seldom 100% loaded, and likewise, seldom 0% loading.

Renewable generation has loading that regularly fluctuates between no load (0%) and full load (100%) and may remain there, at either extreme, for days or weeks at a time.

Utility cables go from substation to substation, transformer to transformer, and seldom need splicing for original installations. Renewables may also have transformer to transformer sections, but almost every collector circuit has a longer cable from the last collection point in the system to a substation. The final "home run" may be tens of kilometers or miles in length, requiring multiple junctions or splices.

3.5 Heating

The heat generated in cables, splices and terminations is created from the current in the circuit flowing through the resistance of the accessory or cable. The cable size is based upon its heat dissipation properties. If it's too hot, the cable can be made larger. Couplings and splices are based upon the same parameters, however they must be constructed and installed properly.

Poor connections create high resistance, which creates a hot spot. The heat produced is a square function (the familiar "I2R" formula) which says when we double the current, the heat created by a poor connection is quadrupled (2 squared, or 2 times 2). A fully loaded renewable cable will therefore have 4 times the heat generated of a utility cable operating at half-loading.

3.6 Thermal Expansion

Aluminum has a coefficient of expansion much greater than copper. When an aluminum connection gets hot, it expands much more than a copper connection with the same temperature change. When it then cools and contracts, it will be much greater change than a corresponding copper connection. Utility cables, commonly operating between about 30% to 60% have nowhere near the thermal change that a renewable cable, regularly cycling between no load and full load, will. This continual heating expansion, and cooling contraction, forces poor connections to "loosen" and increase the gap between the coupling and the conductor. This increases the connection resistance and consequently increases heat produced, which further exacerbates the problem.

3.7 Workmanship

A common root cause analysis (RCA) of failed cable and splice failures has been the detection of poor workmanship from the original installation. If the proper preparation of terminations and cables, as specified by the manufacturers, is not followed, a high resistance joint may occur. This failure mode is not readily visible at the time of installation but is readily visible with a post-failure root cause analysis.

Improper wire preparation is perhaps the most common cause of failure observed in both types of terminations. Usually, such improper preparation shows up with extreme heat in the termination; improper preparation leads to a high resistance connection, which heats up rapidly. Multiple manufacturers have documented that, while improper cable preparation is a rapid cause of failure in compression connectors, shear bolt connectors are inherently much more resilient against this failure mode. Lack of proper preparation is due to poor training, poor knowledge, and poor workmanship. But at the same time, this type of failure isn't seen nearly as often in utility applications.

Post failure examination of cables and terminations regularly show the failure of the electrician to wire brush the surface of the cable and to apply a corrosion preventive inhibitor (usually supplied with the termination). It is common to hear from electricians in the field that they believe that a clean, shiny, surface of an aluminum conductor is an indication that no further preparation is needed. The electrician may not understand that aluminum oxide may be present on a shiny cable even though it is not visible to the human eye and the termination does require further preparation. An electrician only conducting a visual inspection which falsely identifies a cable as ready for use then skipping the brushing and antioxidant application increases the likelihood of future splice failure.

Figure 4 (left) Microscopic examination of a conductor sent to the laboratory for a Root Cause Analysis after a similar cable failed (and was destroyed) in service. Seen is one outer strand of a multi-strand cable, with no evidence of wire brushing, nor of antioxidant. Figure 3 (right) Microscopic examination of an example of a single strand of a similar sized multi-strand wire after wire brushing and application of antioxidant. (Photographs courtesy of Imcorp).

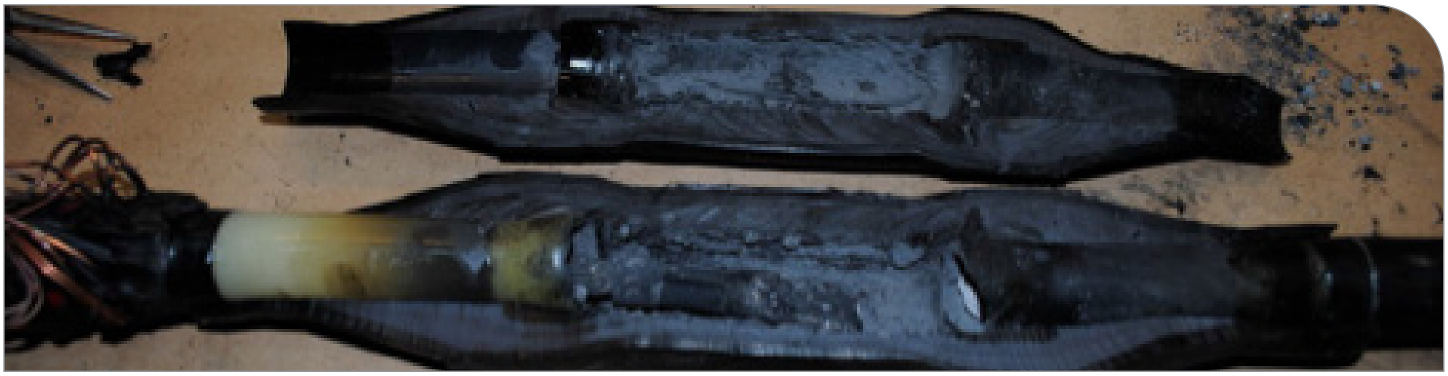

Figure 5 Example of a dissected compression coupling showing extreme heat, burning, and charring. Subsequent dissection of the actual coupling showed no sign of wire brushing (Photograph courtesy of Imcorp).

4 Joint Body Re-creation

After the coupling has been installed, the different layers of the cable must be recreated. Multiple designs are available, including molded (sometimes called "pre molded") push on joints, heat shrink joints, and cold shrink joints.

4.1 Cold Shrink

Cold shrink products are pre-stretched at the factory to allow easy installation over a cable; their shape is held using a mechanical (plastic) retaining core. The products then shrink onto the cables when the core is removed and discarded. The inward pressure from the pre-stretching provides an excellent environmental seal and improves electrical performance.

Cold shrink products can expand and contract with the cable as it responds to different temperatures. Cold shrink is therefore an excellent choice where thermal expansion or contraction from temperature may occur.

4.2 Heat Shrink

Heat shrink products are expanded at the factory above their final permanent setting. High intensity heat shrinks the product to its final set diameter. After the high intensity heat has been removed, the material "freezes" and becomes rigid again. Most heat shrink products use hot melt adhesives and mastics to environmentally seal the cable.

4.3 Pre-Molded Push On

Pre-molded joints are made at the final size and forced, or expanded by hand, onto the cable by the installer. These are not commonly used for renewable applications.

4.4 How Splices or Joints Work

Joints, unlike terminations, must manage all electrical stresses within the joint (or splice). There are three main areas to consider when discussing joints: the electrode area, the insulation, and the insulation shield, part of which is the end seal. The failure to properly recreate any section of the cable will eventually result in a splice failure.

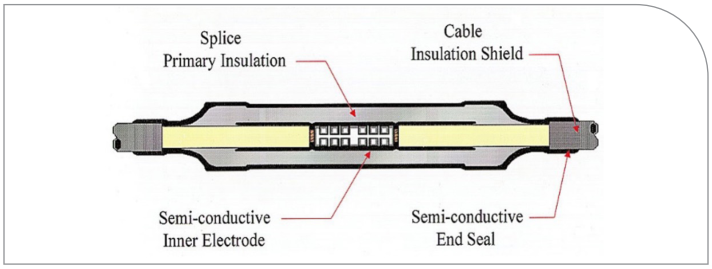

Figure 6 Joint cross section

4.4.1 Semi-conductive Inner Electrode

The most critical area of a joint is the area around the connector itself. The gaps between the coupling and the cable insulation must be filled so that partial discharge does not occur. These gaps are usually handled by creating a Faraday cage around the connector. The Faraday cage transfers potential from the connector to the semi-conductive inner electrode. Once all components are at the same potential, there is no electrical stress, and no chance for partial discharge.

4.4.2 Splice Primary Insulation

The primary insulation must provide adequate electrical insulation but must also be capable of conducting heat away from the connector.

The splice insulation to cable insulation interface is the critical interface area of the joint. Inward compressive pressure at this interface has been shown to greatly enhance the performance of the joint. The higher this interface pressure, the better the electrical performance of the splice. The type of splice material, the length of interference between the splice and the cable insulation, and the type of splice all affect the interface pressure.

4.4.3 Semi Conductive End Seal

The semi conductive end seal is required to replace the insulation shield that was removed during the splice preparation process. Simply put, the insulation shield's purpose in MV cable joints is to allow for an optimized thickness of the insulation. This insulation shield step, often called the cut-back, is where the black semi conductive material that has been removed to expose the insulation, is the most electrically stressed area of the entire joint. The cut back must be perfectly cut back without waves or spurs, and the finished splice must be free of voids. Voids are most often prevented with a dielectric void filling compound (specially formulated silicone grease) or a high-K mastic.

The final purpose of the end seal is to seal the joint to outside elements. The final splice is as environmentally self-contained as the original cable.

The following two tables compare some different parameters that are important between the different joints.

Characteristic	Push on Joints	Heat Shrink Joints	Cold Shrink Joints
Connector dependent	Yes	No	No
100% Factory Tested	Yes	No	Yes – some of them
Installed as one component	Yes – rejacketing installed separately	No	Yes – some jacket included and some jacket installed separately
Type of stress control	Geometric	High dielectric	Typically geometric
Cost	Lowest cost	Medium cost	Highest cost
Interface pressure	Some	Least	Highest

Table 1 Comparison between Push-on, Heat Shrink and Cold Shrink Joint

Property	Extruded Body	Molded EPDM	Molded non-filled silicone	Molded filled silicone
Connector independent	Yes	No	Yes	Yes
Bonded/molded outer insulation shield	No	Yes	Yes	Yes
Insulation outer shield in contact with cable insulation shield	Yes	Yes	No	Yes

Table 2 Comparison of Different Properties of Materials in Joints

4.4.4 Void Filler & Dielectric Grease

Void filler or some type of dielectric grease is a part of all power cable accessory installation kits designed for typical North American cable designs with a strippable outer semicon layer (insulation shield), but its purpose is often misunderstood by installers. In some cases, the void fillers are mastics that have a putty or gum like consistency while others are a grease made of silicone or other flowable polymer like a fluorinated polyester. The most important use of the void filler is to fill voids on the interface between the cable insulation and the accessory or the mating interfaces of separable connectors (elbow or T-body style terminations). A secondary use is to provide a mechanical assist while pushing on premolded accessories and to ensure separable connectors do not seize up and remain operable. Voids and stress enhancements in the presence of sufficient voltage stress gives rise to partial discharge, erosion, electrical treeing and eventual failure. Only the void filler specified by the manufacturer or the product that comes with the kit should be used. This will ensure the void filler has the correct temperature stability and polymeric structure so it will stay in place and not leak out of the accessory or be absorbed into the accessory body during normal operation. Installers should take great care to read the manufacturer's instruction on where to apply void filler. At the very least void filler should fill in the outer semicon cutback step. In many cases a thin layer is also required on the cable to accessory interface or on the interface of separable connector type interfaces. Some joint designs do not have a Faraday cage around the conductor connector (e.g. Prysiman cold shrink joint and Raychem heat shrink joint) and mastic is used as a void filler in this area. Other designs have void fillers preloaded and provided the accessory is placed correctly on properly prepared cable, they will function effectively. ACP recommends you read and follow the manufacturer's instructions and take special note of where the document references "void filler", discharge control compound (DCC)", "dielectric grease", "stress reducing mastic (SRM)", or "lubrication".

5 Final Evaluation

A summary of manufacturers' evaluation findings is captured below.

- High ampacity, high load cycle applications of solar and wind renewable projects have much different operating parameters than do utilities which have more moderate load, low-load cycle operations. Utility cables seldom, if ever, see full loads.
- Cables and connections in renewable applications can see 100% or 0% load for long periods of time. Cables in utility applications usually run in a middle range.
- Compression style connections have been used successfully for years in industrial and utility applications. Utilities have highly trained electricians, who do the same job, with the same parts, and the same tools, on the same size cables, repeatedly.
- Renewable energy projects typically have several different sizes of wire. The electricians will not do the same job, with the same parts, and the same tools, on the same size cables, repeatedly.
- Compression connections have a low up-front cost, and a high failure rate.
- Shear bolt connectors have a higher up-front cost, but a much lower failure rate.
- Compression style connections have, for at least the last decade, been seen to have premature failures when used in renewable applications. Root cause analysis had determined that there are many aspects of these failures which can be directly attributed to human error. Human error can be addressed through education and retraining, but that does not eliminate the possibility of a recurrence. Human error can also be addressed through an engineering solution; the parts and pieces that can cause the error can be eliminated.
- Shear bolt connectors are an engineering solution.
- Shear bolt connectors have been shown to be much more robust in resisting failure when an electrician accidentally, or unknowingly, improperly prepares the conductor and leaves a high impedance connection.
- Shear bolt connectors have a larger mass and transmit heat away from the connection better than compression connectors, thereby running cooler.
- Shear bolt connectors have a more consistent connection than compression connectors.
- Shear bolt connectors cannot be compressed incorrectly and do not deform into a 'banana' shape.
- Shear bolt connectors can leave sharp tabs which must be filed or otherwise taken care of before seating in the rubber goods.

Shear bolt connectors give a more consistent electromechanical connection than compression connectors, at a higher cost. Compression connectors are cheaper to purchase, but under renewable usage are known to prematurely fail – quite regularly. It is up to the user to decide what factors are the most important when deciding which connector to specify.

Table 3 shows some of the basic attributes and offers some objective evaluation of those attributes.

Attributes						
Product	Mass *More mass is better	Ribs or groves *These break through aluminum oxide	Bolt could shear above/below housing *Could need filing to align to protect splice body	Bolt turns against cable strands *May remove/reduce conductor mass	Cost Relative	Comment
Compression	Lowest	No	N/A	N/A	Lowest	Could need to file compression burrs
Multi-shear	Highest	Yes	Yes	Yes	Middle	
Multi-shear pointed	Highest	Yes	Yes *Shear location is less predictable, could need to file shear step significantly	Yes *Penetrates strands	Unknown	
Continuous shear	Highest	Yes	No *Could need to file burrs	No	Highest	

Table 3 Comparison of different solutions, drawbacks, and advantages.

The American Clean Power Association (ACP) is the leading voice of today's multi-tech clean energy industry, representing over 800 energy storage, wind, utility-scale solar, clean hydrogen, and transmission companies. ACP is committed to meeting America's national security, economic and climate goals with fast-growing, low-cost, and reliable domestic power.

Learn more at **www.cleanpower.org**.

Twitter / @USCleanPower

LinkedIn / American Clean Power Association

AMERICAN CLEAN POWER