

The logo for Sargent & Lundy, featuring a stylized grey 'S' shape that curves and tapers at the ends.

Sargent & Lundy

WHITE PAPER

Wind Project Repowering

Best Practices and Insights: Focus on Partial Repowering

Brian Connaghan | Eric DeCristofaro
Eric Soderlund | Matthew Thibodeau | Xuan Wang

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As the global fleet of wind power projects continues to grow and age, repowering is becoming increasingly prevalent.

Recently, partial repowering of wind projects has become an attractive option for many wind project owners in the United States because of tax law changes in December 2015 and the availability of repowering offerings from wind turbine suppliers. Partial repowering enables project owners to capture more energy from their sites, to extend the life and improve the availability of their projects, and to take advantage of extended Renewable Energy Production Tax Credits (PTCs). Partial repowering has been a widespread strategy since 2017.

This white paper highlights best practices, common issues, and insights that Sargent & Lundy has identified during recent wind repowering efforts, with a focus on wind turbine foundations, electrical balance of plant (BOP), and wind turbine towers. Our goal is to support owners, investors, lenders, and engineers on their current repowering projects and to effectively plan for their future repowering initiatives. Our findings are based on a large dataset from 65 projects that underwent repowering, including inspections of over 4,240 wind turbine foundations, structural analyses of six types of wind turbine foundation designs, over 190 tower inspections, and reviews and analyses of numerous electrical BOP systems.

There are many critical considerations when determining whether a wind project is a suitable candidate for partial repowering, such as the integrity and capacity of the foundations, the impact on the plant electrical systems, and the condition of the wind turbine towers. Other important considerations include understanding the energy yield of the repowered wind project, the suitability of the repowered wind turbines for the site, long-term operations and maintenance (O&M) costs, and commercial and permitting impacts. To address these key considerations, Sargent & Lundy has developed a carefully considered methodology founded on both our thousands of hours of analysis from recent wind repowering projects as well as our industry-leading depth of structural engineering experience.

Introduction

In December 2015, the U.S. Internal Revenue Service (IRS) extended the Renewable Energy PTC program. Wind facilities that commenced construction by December 31, 2016, are eligible for the full inflation-adjusted per-kilowatt-hour credit for 10 years from the date they are put into service. Thereafter, PTCs are being reduced by (1) 20% for projects beginning construction in 2017; (2) 40% for projects beginning construction in 2018; and (3) 60% for projects beginning construction in 2019. In December 2019, Congress passed an extension of the PTC allowing wind facilities that commence construction in 2020 to receive 60% of the inflation-adjusted credit. The tax credit applies to both new construction and repowering projects that satisfy the “80/20” rule.

This rule, as defined by the IRS, is that a “facility may qualify as originally placed in service even though it contains some used property, provided the fair market value of the used property is not more than 20% of the facility’s total value.” In other words, the cost of new components divided by the value of the repowered facility must be greater than or equal to 80%. To ensure that a repowering effort meets the IRS guidelines, typically two or more independent consultants are hired to perform valuations of the retained components and to calculate if the 80/20 criteria can be met.

All of the partial repowering projects Sargent & Lundy has been or is currently involved with were able to meet, or plan to meet, the criteria set forth by the IRS to claim the PTC while using, at a minimum, existing wind turbine foundations, wind turbine towers, and electrical BOP.

To date, Sargent & Lundy has experience with partial repowering projects that cover a range of part replacement strategies. Some projects have chosen to reuse yaw systems, nacelles, and generators, while replacing components like blades, hubs, main shafts, main bearings, and gearboxes. Other projects have gone further and replaced all major components above the towers, including blades, generators, yaw systems, and nacelles. Yet another partial repowering variation is the complete replacement of up tower components of one manufacturer with newer technology from a different manufacturer, while retaining the existing towers and foundations.

Partial Repowering Key Considerations

The sections below highlight some of Sargent & Lundy's key considerations during wind repowering projects, highlighting findings that will aid owners, investors, lenders, and engineers with maintaining ongoing operations and planning for successful repowering.

These findings are based on our experience with 65 repowered wind projects. This work involved inspecting more than 4,240 wind turbine foundations, performing numerous wind turbine foundation finite element analyses (FEAs), performing more than 190 tower inspections, and reviewing and analyzing electrical BOP systems for every project.

Wind Turbine Foundations

The integrity and capacity of the existing foundations are the most critical considerations for the long-term success of a repowering effort. Owners and tax-equity investors have demanded a thorough, detailed, and comprehensive review of existing foundations, including strength, serviceability, and fatigue analyses. Sargent & Lundy has established an approach to understand the risk of foundation failure that is based on our thousands of hours of analysis on repowering projects. Key discoveries and outcomes from the extensive modeling we have performed for a variety of wind turbine foundation designs—including octagon spread footing, circular spread footing, foundation mounting part (FMP) spread footing, soil/rock anchor, and Patrick & Henderson (P&H) Tensionless Pier—are discussed below, including our methodology established to assess the risk of foundation failure.

The integrity and capacity of the existing foundations are the most critical considerations for the long-term success of the repowering effort.

Sargent & Lundy's approach developed to determine the risk of wind turbine foundation failure begins with reviewing the original foundation design and, in particular, whether the design was developed with proper consideration for fatigue loading. In addition, we also assess the condition of the exposed (i.e., above-grade) portion of the foundations. Additionally, excavation at a statistically relevant sampling of wind turbines is typically performed in advance of the repowering effort to check for cracks and assess the general condition of the buried portions of the foundations. Following a site visit, we review a project's quality assurance and quality control (QA/QC) documentation to assess the quality of workmanship and adherence to wind turbine and foundation design specifications from initial construction. While this review can be a challenge for plants that have changed ownership and/or have poorly managed document control, Sargent & Lundy can use available information and statistical methods to develop analysis input parameters. Finally, and most importantly, Sargent & Lundy develops a detailed FEA of the foundation design to properly assess its strength, serviceability, and fatigue. Key findings from our extensive modeling for recent repowering projects are described below:

Code Application

The wind turbine foundation analysis and design should be based on ASCE/AWEA RP2011, ACI 318, and IEC 61400-1 standards. For the fatigue check of concrete and reinforcement, Eurocode 2 and DNV OS-C502 should be used.

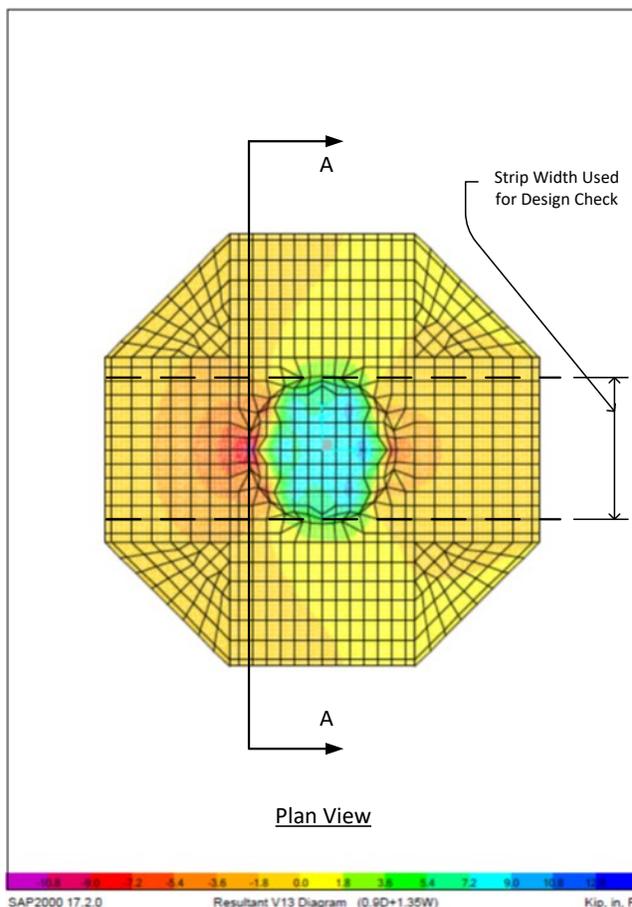
Investigation Tool

An FEA model should be used for the foundations, especially for the fatigue damage check, because it can yield the realistic resultant force distribution and account for the proper stress concentration. Additionally, an FEA is important as other types of analyses using only traditional “hand calculations” based on strict design code application may yield non-conservative results because formulations used may not represent the actual behavior of wind turbine foundations.

Design Strip Width

A common technique used in structural analysis of reinforced-concrete foundations involves selecting a governing strip (design strip) of the foundation to ensure acceptance criteria are met. This simplified

technique heightens focus on the governing (high-stress) section, while the other, lower-stressed sections remain bounded by the governing analyzed design strip. The first step in this analysis is to identify the region of the foundation subject to the highest demand (stress). A design strip width is then selected to capture this high-stress region. For wind turbine foundations, the high-internal-stress region is typically concentrated adjacent to the pedestal, as can be seen in the figure on the left (excerpted from an actual FEA).



For the design strength analyses of spread footings, ACI 318 allows consideration of the full width of footing. However, Sargent & Lundy considers this to be non-conservative, and we maintain that it should not be applied to wind turbine foundation analysis. For this reason, we recommend consideration of a strip with a width equal to that of the pedestal, because it yields realistic analysis results. This recommendation is based on the results of FEAs as well as actual wind turbine foundation investigations Sargent & Lundy has performed of foundations subject to fatigue damage and, in some cases, catastrophic collapse.

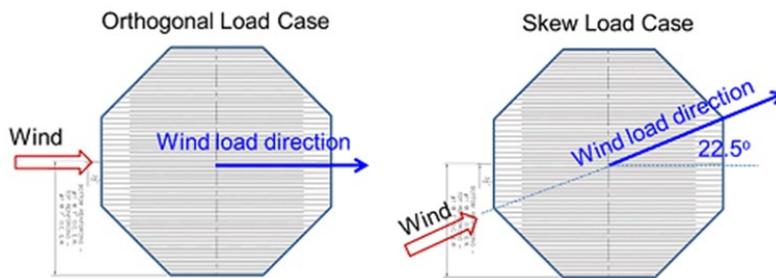
Below-Ground Foundation Inspection

Before repowering, it is important for an engineer to inspect certain portions of wind turbine foundations to set up the baseline for the foundation condition assessment and future inspections. This requires careful excavation. Foundation inspection results provide input for the foundation fatigue damage and design life calculation.

Cracked versus Uncracked Properties

Sargent & Lundy has performed parametric studies using both cracked and uncracked concrete section properties in our FEAs to determine which modeling approach is more conservative for structural evaluation. The parametric study demonstrates that when the footing is modeled as cracked only at the critical location on the footing, the resulting internal stresses at the critical section of the footing are lower (less conservative) than that of the uncracked model. This may be viewed as counterintuitive, but because consideration of partial cracking allows redistribution of stresses in the most highly loaded sections of the foundation, it actually provides less conservative stress redistribution within the model. Additionally, modeling the footing as uniformly cracked through the footing section is unrealistic, as it shows superficially high stresses; yet the overall load distribution of the uniformly cracked model is similar to the uncracked model. Therefore, our use of uncracked FEA results is conservative for performing a structural evaluation of whether a foundation’s capacity exceeds demand.

Skewed Wind Load



For octagonal wind turbine foundation footings with orthogonally oriented reinforcement, we have performed parametric studies that consider a skewed wind-load case to evaluate the flexural capacity of an octagon spread footing foundation’s top and bottom steel reinforcement.

We analyze the skewed load case by considering the wind loading applied at a 22.5° angle (and 45° angle) relative to the reinforcement steel alignment (see figure to the right). We compare the results of the skewed load case with results from an orthogonal wind-load case. The results of Sargent & Lundy’s recent parametric studies have shown that the load case for the orthogonal wind direction governs the design.

Site-Specific Design Loads

Existing foundations are typically designed based on IEC standard loading conditions for a 20-year design life. A repowering analysis should check that the existing foundations are adequate, considering both the life of the foundation up to the repowering and 20 additional years after the repowering. For this reason, Sargent & Lundy recommends that site specific wind loads be developed to conduct foundation design checks.

Exposed Foundation Inspection Findings

During recent repowering projects, Sargent & Lundy has inspected the exposed portion of more than 2,600 wind turbine foundations at sites being repowered. During our inspections, we focus on the pedestal, grout ring, and anchor bolts. We also observe the areas surrounding the base of each pedestal. Numerous recommendations for minor repairs have resulted from these inspections. In general, the exposed portion of the foundations have been in good condition, with some instances of minor deterioration, including pedestal concrete cracking and chipping, minor grout ring cracking and chipping, and anchor bolts exhibiting low levels of surface corrosion with damaged or missing cover sleeves. On some foundations, grout ring damage has resulted in gaps beneath the tower base flanges; this inhibits load transfer from the tower to the foundation and warrants repair. Another common finding at many of the sites was deterioration of the originally established grade around the turbines. Since the weight of the soil is considered to help the foundation resist overturning and sliding forces due to wind, regrading has been required at some locations. Since the necessary equipment for these repairs is typically already on site, a repowering campaign is an opportune time to repair damaged foundation concrete and regrade areas around the wind turbines that may have eroded over the years due to water or wind.

Electrical Balance of Plant



Reusing the electrical BOP can provide substantial costs savings but is not without risk to the project. To assess such risk, an independent engineering evaluation should be performed to assess the suitability of the existing electrical BOP for the repowered wind turbines and the impact of additional years of operating life on the equipment. Evaluations should include a detailed analysis of site drawings, calculations, and reports, along with a site visit to ensure the substation, collection system, control systems, and transmission lines are suitable for repowering. Certain partial repowering variations, including ones that involve changes to the turbine maximum output, generator, reactive capability, or transformer ratings, may require new engineering studies to support the repowering. For example, the following studies may need to be completed: ampacity, transformer loading, reactive capability, short circuit, grounding, relay coordination,

harmonics, and supervisory control and data acquisition (SCADA) coordination. The results of these studies may require new capital upgrades, replacements, or site-specific curtailments to ensure the reliable operation and compliance of the electrical BOP post-repowering.

Based on Sargent & Lundy's experience with partially repowered projects in the last year, areas of focus should include:

Reactive Compensation

Reactive compensation is a key issue within the electrical BOP analysis, as it can have technical, commercial, and financial ramifications. Projects that are increasing their maximum wind turbine power output or changing their wind turbines' reactive capabilities will require a new reactive compensation study for the independent system operator (ISO). Project owners will need to confirm what, if any, changes are required to the interconnection agreement, and if that has any impact on reactive compensation requirements. Depending on the project, the results can range from no upgrades being needed, to new capacitor banks, reactors, or static volt ampere reactive (VAR) compensators being needed to meet interconnection agreement requirements.

Project Expected Life

The additional design life expected from reused components of the electrical BOP must be carefully analyzed for all repowering projects. Considering that wind projects often have 20-year design lives, a partial repowering occurring in Year 19 of a project can represent up to a 100% increase in the desired operating life for certain electrical BOP components. However, the majority of a wind farm's electrical BOP comprises utility-grade designs and components and can reasonably be expected to operate in excess of 30 years. Sargent & Lundy has used our extensive experience with these designs to make site-specific recommendations regarding as-designed electrical BOP lifespan. This includes recommendations that O&M budgets and procedures be revisited as certain components age.

Furthermore, pad-mounted transformers and collection system splice failures should be analyzed as an indicator of potential electrical BOP costs going forward post-repowering. In addition, site-specific load profiles can be developed to analyze heat-related aging of components, such as cables, main transformers, and pad-mounted transformers. To date, Sargent & Lundy has not observed major electrical BOP capital expenditures because of partial repowering projects.

Ampacity Overload Analysis

Any time that turbine output is increased, a plant's entire electrical BOP needs to be reviewed to ensure ampacity limits are not exceeded. The critical elements include pad-mounted transformers, collection system cables, and current-carrying elements of the substation. In Sargent & Lundy's experience, pad-mounted transformers and collection system cables are the most likely elements to have inadequate ampacity for a project's uprating. We are familiar with several options that can be utilized to provide additional refinement of engineering calculations and to verify transformer and cable adequacy:

- **Thermal Considerations:** Wind power plants are typically designed assuming 100% load factor on current-carrying elements. This conservative assumption can be refined through calculations to consider the cyclical nature of wind power plants and their effect on equipment overheating. Ampacity increases of 10% are common when this type of refinement is utilized, including additional capacity on both the transformers and cables.
- **Losses:** If transformers/cables are overloaded, accounting for reactive and resistive losses in the collection system should be considered. Specifically, on transformers close to their ampacity limits, the effect of reactive losses within a transformer can be considered to bring the current at the output terminals under the transformers' nameplated limits.

- **Generation and System Voltage:** Full-load flow studies can be run to include system wide voltages, reactive capability curves, equipment limits, and power flow that will refine the current carried by individual elements. Sargent & Lundy's extensive experience with these types of calculations has allowed certain components to be qualified even when conservative and high-level calculations would cause them to initially appear overloaded.

If engineering calculations show that ampacity criteria cannot be met, projects can choose to curtail generation of certain turbines or to modify turbine strings to ensure the ampacity ratings of specific cables or transformers are not exceeded.

Harmonics / Subsynchronous Resonance

Power quality and subsynchronous resonance (SSR) are concerns with any interconnection, so they should also be monitored for partial repowering projects. Typically, confirmation from original equipment manufacturers (OEMs) can be obtained that the components replaced by the partial repowering will have no effect on harmonic distortion or SSR, meaning no additional study or mitigation is required. However, these issues will need to be evaluated on a case-by-case basis for repowering projects that replace components—such as power electronics, capacitor banks, and transformers—that can have an effect on harmonic distortion or SSR.

Interconnection Agreement

Understanding how repowering will impact compliance with an interconnection agreement (IA) is a critical element of a partial repowering project. Initially, a project needs to determine if its existing IA and interconnection studies will remain valid post-repowering. Depending on the project scope, the entire IA and all its associated studies may need to be redone, potentially leading to a delay while the project progresses through the interconnection queue with the ISO. This scenario can also expose the project to the possibility of updated and potentially more stringent interconnection requirements as well as the possibility of additional payments to the interconnection utility for system upgrade costs. If it is determined that the existing IA and interconnection studies are valid, the project must still confirm that all the IA's technical requirements are being met and submit updated documentation of the planned upgrades to the ISO and/or interconnecting utility. In Sargent & Lundy's experience, existing IAs and interconnection studies have been found to be applicable and valid by the appropriate stakeholders post-repowering.

Wind Turbine Towers

Partial repowering efforts in the United States to date have elected to reuse existing wind turbine towers. In general, the towers observed by Sargent & Lundy at repowering candidate sites, which have been from nine to 18 years old, have been in good condition and considered suitable for repowering. However, there have been projects where towers have failed in the past. So, it is important to assess the condition of the towers both externally and internally via tower climbs to ensure that the towers are in good condition and properly maintained. In addition, documentation, including analyses and certifications of the repowered turbines, pre-upgrade (i.e., pre-repower) inspection certificates, and existing procedures and maintenance records should be reviewed. To date, findings from tower reviews have been largely site-specific and have not required large capital expenditures. Some key generic findings—based on our tower inspections of over 120 wind turbines and our tower documentation reviews—that should be considered are discussed below:



Mechanical Loads Analysis: A project's owner needs to provide direction to the wind turbine OEM when performing turbine component loading analysis to ensure that the appropriate duration of baseline operation is considered within the analysis. For example, analyses performed six months to a year prior to repowering turnover did not consider the component loading over the interim period between completion of the analysis and repowering completion.



Protective Coating Maintenance: A tower coating monitoring plan should be in place to monitor, document, and disposition coating degradation of the exterior and interior wind turbine tower walls.



Anchor Bolt Maintenance: Anchor bolt tensioning procedures should be in place to periodically confirm that the anchor bolts are tensioned in accordance with the foundation design technical specifications. Procedures should indicate an interval for inspection and provide a means for technicians to classify and remediate any anchor bolt corrosion.

Wind Resource Assessment

Performing a wind resource assessment based on a repowered configuration reduces the uncertainty in a project's forecasted power generation and associated revenue. As a part of the assessment, the increase in gross energy production on an annual basis and, in some cases, a monthly basis can be determined using existing and proposed power curves and a best estimate of wind frequency distribution. In general, a wind resource assessment should include an uncertainty analysis, including P50, P75, P90, P95, and P99 estimates of net energy for use in a project's financial models.

While repowering efforts typically involve replacing existing blades with longer blades able to capture more energy from the wind, these may also result in increased wake losses and wake-induced turbulence. For this reason, appropriate wind resource assessment software should be used to establish differences in wake losses between the original and repowered turbine configurations.

Finally, a thorough wind resource assessment of a repowered site should be able to provide an accurate prediction of power generation with more certainty than a project's original pre-construction assessment, due to the additional wind data available from years of operating the wind power plant.

Wind Turbine Technology and Site Suitability Review

A review of the repowered technology incorporated as a part of the updated configuration should be performed to assess potential implications of the combination of existing components and new components. An example of this scenario is whether a project's existing yaw drives can handle higher loads from a new larger rotor. Industry experience with primary replacement components should be reviewed to identify potential issues that may result from the combined use of existing and new equipment. Then, the wind turbine manufacturer's approach to resolving any problems should be assessed. The review should also consider sequencing effects of wear and fatigue damage on components that are not planned to be replaced. This review is especially important in cases when the original wind turbines from one manufacturer are being partially repowered with new components from a different wind turbine manufacturer.

Commercial and Permitting Review

Prior to repowering, a review of commercial agreements and permitting requirements should determine that operating and technical requirements of applicable agreements and contracts will be met post-repowering. The review should include existing approvals, permits, and licenses to confirm that a repowered plant can operate in full compliance and that there are no limiting restrictions after the commercial operation date (COD). Extending the life of a wind power plant through partial repowering typically pushes the anticipated project life past the expiration dates of important contracts, such as power purchase agreements (PPAs). Sargent & Lundy recommends that appropriate sensitivities be considered in any financial models when projecting revenue beyond the expiration date of such contracts. To understand the appropriate sensitivities and risks, it is important to rely on experienced industry professionals. To reduce the risk of non-compliance, the IA should be reviewed in detail if a generating capacity increase is planned. Several federal legal authorities, including the Federal Aviation Administration (FAA), U.S. Army Corps of Engineers (USACE), U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency (EPA), and state and county legal authorities may impose additional permitting requirements that need to be considered. To avoid unexpected delays and/or fines, a permitting specialist with relevant experience should be consulted. During recent repowering projects, our permitting review has been performed alongside our commercial review.

Operations & Maintenance Cost Assessment

Projected O&M costs following repowering through the end of a project's life should be assessed for agreement with its financial model to evaluate the level of risk to project stakeholders. This assessment should include a review of existing operations, maintenance, and management agreements in place; a review of historical operating costs for a project; and an assessment of O&M cost escalation for similar operating wind projects. The review should also include assessments of unplanned maintenance caps relative to historical major component failure rates. A buildup of anticipated annual project costs can be calculated based on a review of operating cost data gathered from similar projects. For this, Sargent & Lundy relies on our internal O&M project cost and performance database, which includes cataloged capital cost, operating cost, and performance data from our experience on over 200 wind projects.

Summary

For the long-term success of any partial repowering effort, the integrity and capacity of a project's existing wind turbine foundations are the most critical of the key considerations. Sargent & Lundy has developed a carefully considered methodology founded on both our thousands of hours of analysis across our recent wind repowering projects as well as our industry-leading depth of structural engineering experience. This depth of experience is the result of our staff of over 200 structural engineers, including many with a PhD and/or advanced degrees who actively sit on relevant code committees, such as for ACI 351 (Rotating Equipment Foundations), AISC TC9 (Seismic), ASCE (Turbine Foundations), and ACI 307 (Shrinkage Compensating Concrete – Past, Present, and Future).

Sargent & Lundy's wind project partial repowering approach has withstood rigorous debate and numerous rounds of industry review. To further mitigate the risk of repowering, we have developed and implemented wind project electrical BOP and tower review processes that yield value in reduced risk to stakeholders while facilitating smooth repowering campaigns. Owners, investors, lenders, and engineers are encouraged to leverage the experience and findings shared in this white paper to navigate a more efficient, well informed repowering campaign. With more than 125 years of experience in the power generation industry, a culture of quality and attention to detail, and a diverse staff of experienced engineers and financial experts, Sargent & Lundy is the right choice to support wind repowering projects.

About Sargent & Lundy

Sargent & Lundy is one of the oldest and most experienced full-service architect engineering firms in the world. Founded in 1891, the firm is a global leader in power and energy with expertise in grid modernization, renewable energy, energy storage, nuclear power, and fossil fuels. Sargent & Lundy delivers comprehensive project services—from consulting, design, and implementation to construction management, commissioning, and operations/maintenance—with an emphasis on quality and safety. The firm serves public and private sector clients in the power and energy, gas distribution, industrial, and government sectors.

For more information, please contact:
Matthew R. Thibodeau | Senior Vice President
+1-312-269-7633 | mthibodeau@sargentlundy.com