Manufacturing Industrial Development for the Alternative Energy Systems

Final Report

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Manufacturing Industrial Development for the Alternative Energy Systems – a DOE/NCMS Partnership

Project Period: November 1, 2009 to October 31, 2012

Recipient: National Center for Manufacturing Sciences
Award Number: DE-EE0000271

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1.1 Background

NCMS has expertise in identifying, developing and demonstrating science-based manufacturing processes, test/diagnostics, and efficient assembly solutions. NCMS also uniquely adds value by rapidly “catalyzing” collaborations, technology transfer and integration programs for manufacturing technologies. NCMS has a 26-year history of creating robust, market-oriented public and private partnerships in the national interest, addressing current and anticipated manufacturing issues emerging from many new technologies, including the manufacturing of alternative energy technologies. As a premier provider of collaborative research, information, knowledge and expertise to the North American manufacturing and defense community, NCMS has spearheaded numerous technology developments. These include advanced materials, machine tools, automation, electronics, high performance machining, process control, rapid prototyping/manufacturing, enterprise integration, information security and environmental technologies – all focused on enhancing the nation’s manufac-

turing competitiveness in the global economy. NCMS has been working with many of its 200+ members and nonmember companies as well as state and federal agencies involved in alternative energy development.

1.2 Objective

For this initiative, NCMS identified and developed critical manufacturing technology assessments vital to the affordable manufacturing of alternative energy systems. NCMS leveraged technologies from other industrial sectors and worked with its extensive member organizations to provide DOE with two projects with far-reaching impact on the generation of wind energy.

1.3 Tasks and Deliverables

This 36-month program included the following task and subtasks:

Manufacturing Technology Development and Implementation – Develop and implement collaborative development projects amongst technology providers, commercializing companies, and end-users that addressed the manufacturing technology issues deemed of highest impact. (month 12-36).

NCMS estimated two projects would be initiated and completed:

- Each project would have a distinct set of deliverables in addition to a final project report.
- NCMS had in place a robust, disciplined and structured process for soliciting and managing collaborations between industry, trade groups, academia and government. This process was used in the previous NCMS/DOE program.

- Project ideas would be solicited through the NCMS newsletter, directed e-mailings, through publicity at selected conferences, and other mechanisms suggested through the workshops and interactions with the DOE program manager.
- Project ideas would then be developed into specific proposals by the collaborative project team, outlining the nature of the manufacturing problem, the specific approach to be taken, performance metrics and benefits analysis, a thorough safety and risk assessment, hard deliverables (beyond project reports), qualified cost share information, identification of the participants and their specific roles/tasks, and project costing and timelines.
- Each project would primarily follow a pilot project strategy to be used as the management of change process for ensuring technology transfer.
- NCMS would work with the DOE program manager to review the proposals and reach a go/no-go decision on each effort.

Deliverables for the program were:

- Project proposals to address the key manufacturing issues for affordable systems.
- Each collaboration development project would have a final report.

NCMS has a strong history of working in partnership with the federal government, working closely with DOE staff to augment other efforts being undertaken by the Department to avoid any duplication. This program uniquely addressed manufacturing issues that will be faced in the widespread production of alternative energy systems.

1.4 Soliciting Project Ideas

The following call for project ideas was issued on March 4, 2010:

“NCMS is partnering with the Department of Energy to identify and develop critical manufacturing technologies vital to the affordable manufacturing of alternative energy systems. We are issuing a call for Concept Papers which will be used to select projects to be funded by this program.

NCMS is interested in Concept Papers in the following areas:

- Advanced composite manufacturing technologies that will enable process automation for wind blade manufacturing including process automation and advanced curing technologies for higher throughput.
- Advanced joining technologies to reduce the cost of manufacturing and installing wind turbines.

Collaborations are expected.”

1.5 Timeline for Project Ideas

Two page Concept Papers needed to be mailed to Chuck Ryan, chuckr@ncms.org by 5:00 p.m. EST, March 31, 2010. Selected teams would be asked to develop a larger proposal (12-15 pgs.)

The project idea call went out via email to over 4,300 people, and an additional 500 were informed via Twitter.

In response to the call, 26 project teams submitted ideas. Table 1 lists project titles and submitting organizations. Appendix A contains the ideas submitted to NCMS in response to this call for project ideas.

Table 1. Submitted Concept Papers

Project Idea #	Title	Submitting Organization
1	Hybrid Laser/Gas Metal Arc Welding for Wind Tower Manufacturing	AMET
2	Long Service Life, Reliable Composite Wind Turbine Blades	Pacific Engineering
3	Hybrid Laser Arc Welding (HLAW) for Manufacture of Wind Towers	GE
4	CAD-Driven Rapid Digital Tooling Application for Manufacturing of Composite Wind Blade Shapes	SIS
5	Wind Turbine Blade Fabrication Automation	Ashland Performance Materials
6	Utilization of Carbon in Wind Turbine Blades Manufacturing Using the "Fibramatic" Technology	Gamesa Wind US
7	A Cellular Carrier Composite Molding Process (C ³ M) for Molding Composite Wind Blades	Global Composite Solutions
8	Advanced Manufacturing Technologies for Wind Blade Manufacturing of Horizontal and Vertical Axis Wind Turbines	LightWeightStrategies LLC
9	Hybrid Laser-GMA Welding of Wind Towers	ARL Penn State
10	Laser Welded Wind Turbine Blades	ARL Penn State
11	Optimized Carbon and Glass Fiber Reinforced Wind Turbine Spar Caps Using Continuous Reverse Pultrusion Production	Profile Composites
12	Laser Guidance for Alternative Energy Systems	Assembly Guidance
13	Design Portal for Rapid Assessment of Wind Blade Design in Support of Advanced Manufacturing Concepts	Alpha STAR Corporation
14	Adhesive Bonding of Composite Towers	Ershigs
15	Automated Inspection System for Wind Turbine Blades	UMich
16	Monitoring System for Wind Turbine Blades	UMich
17	Advanced Processing of Composites for Windmill Blade Manufacturing	AvPro
18	Advanced Control for Use in Processing of Composites for Windmill Blades	Rockwell Automation
19	Next Generation Wind Blade Materials and Manufacturing Technologies	UMaine
20	Automated Process for Application and Curing of a New Safe 100% VOC Free Coating System	Vulcan Catalytic Systems
21	New Manufacturing Method to Rapid Produce Wind Blade Spars with Increased Strength and Fatigue Performance	Fulcrum Composites
22	Low Density Composites for Wind Blade Manufacture	Fulcrum Composites
23	Advanced Manufacturing Processes and Logistics Improvements in the Manufacture and Remediation of Wind Turbine Blades	MRI
24	On-the-Fly Consolidation and Cure in Thermoset Tape Laying Processing	UDelaware
25	Methods to Improve the Manufacturing Quality of Wind Turbine Blades	Triton Systems
26	Electrokinetic Wind Energy Generators	Accio Energy

The following point criteria was used to evaluate the project ideas submitted:

Technology	
Revolutionary – Having the effect of completely changing the nature of material design and build.	20

Evolutionary – The mechanism of existing materials changing towards the "next" logical level.	1

Criticality Rating	
Critical – Technology directly and significantly leads to achieving documented capability. Capability will not be met without this technology.	10
Essential – A significant enabling technology which directly leads to achieving documented capability. Achieving capability is at high risk without this technology.	8
Important – Technology is projected to provide significant margin over current capabilities and is required to support future capability.	6
Contributing – Provides some support (either directly or indirectly) to achieving future capability and/or contributes to maintaining capabilities.	4
Little to No Value – Value to currently documented future capabilities is unclear or not supportable.	1

Strength of Collaboration	
Strong – Team in place to take the technology to the marketplace	10
Potential – Most of the team in place, missing a non-critical member	8
Marginal – Most of the team in place, missing a critical member	6
Weak – Minor collaboration and no relationship with eventual commercializer for the technology	4
No Collaboration in Place	0

Applicability to Other Industries	
Broad Applicability – Technology being developed can be deployed to a wide segment of industrial sectors beyond wind energy	10

No Applicability – Beyond the wind energy industrial sector.	1

Using these criteria, each of the 26 project ideas were rated, and the top five teams were asked to submit a full proposal. Some of the project ideas were similar in scope, so those teams were asked to collaborate on the proposal. This is indicated in those project ideas grouped together in Table 2.

Table 2. Top Project Ideas Grouped

Idea #	Project Idea Title
26	Electrokinetic Wind Energy Generators
21	New Manufacturing Method to Rapidly Produce Wind Blade Spars with Increased Strength and Fatigue Performance
11	Optimized Carbon and Glass Fiber Reinforced Wind Turbine Spar Caps Using Continuous Reverse Pultrusion Production
10	Laser Welded Wind Turbine Blades
8	Advanced Manufacturing Technologies for Wind Blade Manufacturing of Horizontal and Vertical Axis Wind Turbines
3	Hybrid Laser Arc Welding (HLAW) for Manufacture of Wind Towers
1	Hybrid Laser/Gas Metal Arc Welding for Wind Tower Manufacturing
9	Hybrid Laser-GMA Welding of Wind Towers

Three project teams met the deadline for submitting a proposal:

Idea #	Title of Proposal	Submitting Company
8	Advanced Manufacturing Technologies for Wind Blade Manufacturing of Horizontal and Vertical Axis Wind Turbines	LightWeightStrategies
3, 1	Hybrid Laser Arc Welding (HLAW) for Manufacture of Wind Towers	GE/AMET
26	Advanced Manufacturing for Modular Electro-Kinetic (E-K) Wind Energy Conversation Technology	Accio Energy

Again using the project criteria described earlier, these three proposals were graded and ranked:

Rank	Title	Total Points
1	Advanced Manufacturing for Modular Electro-Kinetic (E-K) Wind Energy Conversation Technology	31.33
2	Hybrid Laser Arc Welding (HLAW) for Manufacture of Wind Towers	27.33
3	Advanced Manufacturing Technologies for Wind Blade Manufacturing of Horizontal and Vertical Axis Wind Turbines	26.67

This entire process was reviewed with the DOE field office, and the top two project ideas were the focus of this development program and are featured below.

1. Advanced Manufacturing for Modular Electro-Kinetic (E-K) Wind Energy Conversion Technology

Wind energy is viewed as an important part of increasing the use of renewable energy in the U.S. Today wind turbine technology is quite mature and future developments are largely focused on increasing unit size. However, this will not only present challenges in terms of materials and design for increasing fatigue loading concerns, but also to objections

associated with visual impact, noise, wildlife safety and other local issues. These challenges will only be magnified as remote wind locations are developed and wind farms are located closer to population centers.

Electrohydrodynamic (EHD) wind energy conversion has the potential to enable major expansion in distributed wind energy used by industrial customers. The goal of this project was to validate that a modular wind energy technology based on E-K wind energy

principles and employing established automotive high volume manufacturing techniques and modular platform design concepts that could result in significant cost reductions for wind energy systems at a range of sizes from 100kW to multi-MW.

The objectives of the project were:

- Verified test results that validates that the core technology can produce output equivalent to 30W/m².
- Manufacturing roadmap product plan detailing high volume, precision manufacturing technologies such as those used in the automotive sector can be implemented for E-K wind system fabrication.
- Validated cost model showing that costs lower than conventional wind turbines can be achieved in community and offshore wind applications based on a modular E-K wind energy technology platform.

This work combines science and technology ranging from basic (droplet characterization and processing modeling) to applied (innovative manufacturing techniques) to create a new renewable energy capability. This effort is highly innovative in applying 21st century enabling technologies in charged droplet production, control and power engineering to an entirely different physical approach to wind energy. The key technological advance has been demonstrating the feasibility of E-K wind energy to supply meaningful amounts of wind energy.

Project Executive Summary

The Advanced Manufacturing for Modular Electro-Kinetic (E-K) Wind Energy project, with performers Accio Energy, Inc. and The Boeing Company focused on integrating technology development and manufacturing technology and planning for the development of a disruptive E-K wind energy technology; EHD

wind energy. EHD is a non-turbine wind energy generation technology to deliver clean, sustainable energy to people around the globe. The objective of the project was to demonstrate the commercial viability of the core wind energy generation technology and to identify key manufacturing approaches. These have been accomplished.

What is EHD Wind Energy Technology?

EHD wind energy technology is not based on electromagnetic physics, rather the systems operate on a principle of charge separation in which the kinetic energy of the wind is used to drive positive charges, carried on ambient or supplied charge carriers, away from their negatively charged source, to harvest wind energy.

EHD wind energy is a form of non-turbine wind energy conversion which does not operate based on electromagnetic physics, but exploits electro-kinetic principles, directly converting kinetic energy to electricity. EHD systems emit small amount of water as an electrically charged mist, then uses wind energy to push these charges away from their source, against the electric field that arises from the charge separation. The wind's kinetic energy is converted to high voltage direct-current energy to supply power to users. The EHD system is analogous to a wind-driven capacitor that produces a continuous usable current rather than a discharge. A load applied to the circuit harvests the usable current. An even more potent analogy may be the thunderstorm. In a thunderstorm, high speed rotational winds impose electrical charge on droplets through poorly understood tribo-charging methods. Driven by thermal gradients between the top and the bottom of the clouds (which are driven by their heights of up to approximately 15km), these charges separate. Again, the mechanisms are the subject of scientific debate, although it seems to be generally agreed that it is driven by the varying rates at which water droplets and ice particles move up and down in the clouds and their

varying charge to mass ratios. The tops of the clouds become highly positively charged, while the bottoms are highly negatively charged – in effect, they are large capacitors. When the breakdown voltage of the dielectric (the moist air in the cloud) is reached, a lightning bolt results.

An EHD wind system is “an engineered thunderstorm” in the sense that we want to take that process, operate it at the “normal” wind speeds prevailing 50-300 feet above the ground, and harvest energy continuously rather than intermittently. This is accomplished by emitting a controlled spray of very small droplets with a specific positive charge to mass ratio into the wind. These droplets are pushed to ground by the wind, against the opposing system electric field which is the result of the separation of the positive charges from their negative counterparts. The origin side of the system rises to a high negative potential. When the desired system potential is reached (~150kV) a load is applied, and excess current is drained from the system, resulting in a high voltage direct current (HVDC) generator, as shown in Figure 1.

EHD wind energy conversion has the potential to enable major expansion in wind energy use by major utilities, wind farm developers, and

industrial customers, drastically reducing greenhouse gas emissions, transmission losses, and new transmission capacity requirements. Key to this is the potential for EHD wind to be:

- As modular as solar panels, yet cost competitive with large wind and fossil fuel based generation.
- Visually inconspicuous, silent in operation, and safe for wildlife.
- Fabricated using recycled materials and manufacturing capacity well established within the United States (U.S.).

Like solar panels, EHD wind energy systems are composed of modular panels of fixed capacity (e.g., 5kW), which can be assembled in multiples to produce a desired system output. Thus a 50kW system would incorporate ten 5kW modules, while a 500kW system would employ one hundred modules. Like solar systems, these modules would be sold to developers in any quantity required. By replacing literally dozens of complex, low volume wind system products with three or four standard modules with outputs ranging from perhaps 2kW to 20kW per module, product volumes will increase dramatically, allowing enormous economies of scale.

Figure 1. EHD Wind Energy Operation

Goal

The goal of this project was to demonstrate that a modular wind energy technology based on EHD wind energy principles and employing automotive heritage high volume manufacturing techniques and modular platform design concepts can result in significant cost reductions for wind energy systems at a range of sizes from 100kW to multi-MW.

Tasks associated with this goal were:

- Task 1 – Demonstrate operation of a spray device capable of delivering 0.25 to 2MW for a single orifice.
 - Accio Energy, 5 months.
- Task 2 – Conduct testing of alpha scale E-K wind system in a laboratory environment, using non-custom spray devices. Demonstrate output equivalent to 30W/m².
 - Accio Energy, 4 months.
- Task 3 – Develop manufacturing technology concept for high volume, low-cost, precision tubing incorporating spray devices capable of delivering droplet size and charge density required for E-K wind generation.
 - Accio Energy, 3 months.
 - Boeing, 3 months.
- Task 4 – Develop a preliminary system design concept suitable for use in developing a system cost model, and a roadmap with milestones for product development and launch.
 - Boeing, 3 months.
- Task 5 – Project Management: Track progress, provide deliverables, interim and final report, in-kind accounting and maintain contract compliance.
 - Accio Energy, 12 months.

Accomplishments

During this project, the Accio/Boeing team made major progress on validating the EHD wind energy technology as commercially viable in the wind energy sector, and moved along the manufacturing readiness axis with a series of design changes that increased net system output.

Some accomplishments include:

- 10X increase in power density in prototype performance.
- Achieved system operating voltages over 200kV (from <80kV), a critical hurdle level for achieving high system output.
- Increased net electrical power gain from 10X to 50X the power used to charge droplets.
- Developed world-class first ever 3D multiphysics model of EHD wind energy technology to direct innovation.
- Using 3D model, identified key innovations in droplet formation and charging approach required to achieve target output of >100W/m².
- Validated 3D model using current spray source technology to verify that the model results projecting commercially viable output are reliable.
- Prototyped test hardware that is more readily manufacturable than previous generation hardware, with improved total energy output performance.
- Worked with Boeing to ensure that design concepts leveraged advanced prototyping technologies and retained a high degree of future manufacturability.

As a secondary benefit to this effort, Accio Energy made the following commercialization related achievements during the course of this project:

1. Built strong connections with world leaders in the wind industry (GE, Siemens, EDP Renewables).
2. Conceptualized an entirely new application of E-K energy conversion with applications to industrial pollution mitigation.
3. Developed key understanding of manufacturing to market strategy which produced a much more developed and focused capital efficient plan.

A detailed final report for this project is included in Appendix B.

2. Hybrid Laser Arc Welding for Manufacture of Wind Towers

The goal of this research project was to reduce the cost of manufacturing wind towers through the introduction of hybrid laser arc welding (HLAW) into the supply chain for manufacturing wind towers. HLAW has the potential to enhance productivity while reducing energy consumption to offset the foreign low-cost labor advantage and thereby enhance U.S. competitiveness. HLAW technology combines laser welding and arc welding to produce an energy efficient, high productivity, welding process for heavy manufacturing. This process leverages the ability of a laser to produce deep weld penetration and the ability of gas metal arc welding (GMAW) to deposit filler material, thereby producing stable, high quality, welds on joints with gaps and mismatches typical of those seen in heavy manufacturing.

The project tasks were:

- Test HLAW as a manufacturing technique for 80m wind towers. While HLAW has been utilized for the automotive and aerospace industry, this will be a new use of HLAW for materials approaching 1" thickness.

- Development of adaptive control schemes for thick section HLAW. Modification to welding controllers is anticipated to enable single-pass HLAW for the wall thicknesses seen in tower welding.
- Establish a pilot site in utilization of HLAW for thick wind towers.

It was anticipated the welding productivity that is obtained by switching from conventional SAW welding to HLAW welding is 80% for a standard 80m tower and there will be a significant reduction in consumables because the joints that can be welded are much narrower than that produced by SAW welding. By developing the advanced manufacturing technology required to improve domestic manufacturing capacity and by developing the design tools to optimize designs, this project has provided a technological lead for the U.S. in advanced wind energy technologies by improving productivity and reducing manufacturing costs for wind towers, reduce amount of imported energy and reductions in energy-related emissions.

Project Executive Summary

The goal of this research project was to demonstrate the feasibility of wind tower manufacturing cost reduction through introduction of hybrid laser arc welding (HLAW) joining processes. Such advancements could enable increases in the U.S. competitiveness in alternative energy manufacturing.

Main Findings

HLAW processes have the ability to significantly reduce joining costs, reduce welding cycle times, and enable higher process throughput. These benefits are attained by redesigning the tower joint so that a high power laser can be utilized and the number of weld passes and consumable usage can be reduced.

Outcome or Results

Wind towers utilize varying thicknesses of steel throughout their structures to meet the mechanical load requirements while keeping material costs low. A typical tower might have as many as twelve different material thicknesses. Joining each thickness requires a unique joint design and welding approach to enable the management of quality, productivity, and mechanical properties. In this project, laser joining of materials with thicknesses ranging from 12mm to 35mm were evaluated against the standard quality and mechanical requirements for GE wind tower components. The joining processes demonstrated showed the ability to meet key requirements with the appropriate process controls in place.

Benefits

The strength of laser-based processes for structural steel welding applications lies in the ability of these processes to deliver joining productivity enhancement. For the material thicknesses evaluated over the course of this

investigation, both joining time and consumable usage was documented. An analysis of these values against the baseline data from conventional welding processes used to join tower sections showed savings in joining time and consumables volumes of between 45% and 76% depending on the material thickness.

Technology Transition with Deployment Recommendations

GE has explored many avenues towards commercialization of the technology demonstrated in this study. At the time this project was completed U.S. domestic wind turbine sales were low and the market conditions do not support near term productivity NTI projects for tower structures. The manufacturing readiness level for the processes demonstrated in this project is projected to be at MRL 5. The next step in technology deployment would be to demonstrate welding capability in a factory environment with tower scale components.

A detailed final report for this project is included in Appendix C.

Appendix A – Project Ideas Submitted to NCMS

Project Idea #	Title	Submitting Organization
1	Hybrid Laser/Gas Metal Arc Welding for Wind Tower Manufacturing	AMET
2	Long Service Life, Reliable Composite Wind Turbine Blades	Pacific Engineering
3	Hybrid Laser Arc Welding (HLAW) for Manufacture of Wind Towers	GE
4	CAD-Driven Rapid Digital Tooling Application for Manufacturing of Composite Wind Blade Shapes	SIS
5	Wind Turbine Blade Fabrication Automation	Ashland Performance Materials
6	Utilization of Carbon in Wind Turbine Blades Manufacturing Using the "Fibramatic" Technology	Gamesa Wind US
7	A Cellular Carrier Composite Molding Process (C ³ M) for Molding Composite Wind Blades	Global Composite Solutions
8	Advanced Manufacturing Technologies for Wind Blade Manufacturing of Horizontal and Vertical Axis Wind Turbines	LightWeightStrategies LLC
9	Hybrid Laser-GMA Welding of Wind Towers	ARL Penn State
10	Laser Welded Wind Turbine Blades	ARL Penn State
11	Optimized Carbon and Glass Fiber Reinforced Wind Turbine Spar Caps Using Continuous Reverse Pultrusion Production	Profile Composites
12	Laser Guidance for Alternative Energy Systems	Assembly Guidance
13	Design Portal for Rapid Assessment of Wind Blade Design in Support of Advanced Manufacturing Concepts	Alpha STAR Corporation
14	Adhesive Bonding of Composite Towers	Ershigs
15	Automated Inspection System for Wind Turbine Blades	UMich
16	Monitoring System for Wind Turbine Blades	UMich
17	Advanced Processing of Composites for Windmill Blade Manufacturing	AvPro
18	Advanced Control for Use in Processing of Composites for Windmill Blades	Rockwell Automation
19	Next Generation Wind Blade Materials and Manufacturing Technologies	UMaine
20	Automated Process for Application and Curing of a New Safe 100% VOC Free Coating System	Vulcan Catalytic Systems
21	New Manufacturing Method to Rapid Produce Wind Blade Spars with Increased Strength and Fatigue Performance	Fulcrum Composites
22	Low Density Composites for Wind Blade Manufacture	Fulcrum Composites
23	Advanced Manufacturing Processes and Logistics Improvements in the Manufacture and Remediation of Wind Turbine Blades	MRI
24	On-the-Fly Consolidation and Cure in Thermoset Tape Laying Processing	UDelaware
25	Methods to Improve the Manufacturing Quality of Wind Turbine Blades	Triton Systems
26	Electrokinetic Wind Energy Generators	Accio Energy

Project Idea #1

1. **Project Title:** Hybrid Laser/Gas Metal Arc Welding for Wind Tower Manufacturing
2. **Date:** March 31, 2010
3. **Submitted by:** AMET, Inc., 355 Dividend Drive, Rexburg, ID 83440;
POC: Art Beck, art.beck@ametinc.com, (208) 557-7417
4. **Approximate Start Date and Duration:** May 2010 to November 2010
5. **Statement of Problem:** Wind Tower Fabrication output is growing at a rate that will not meet the targets of the U.S. Wind Energy Roadmap. A transformational change in joining technology is needed.
6. **Proposed Solution:** AMET is a major U.S. provider of automated welding controls and systems to commercial and government customers in the U.S. and internationally. We employ state-of-the-art electronic technologies in our systems (www.ametinc.com) and we have a proven track record of enhancing process performance through technology, and through unique control capabilities in welding with multiple processes and multiple arcs. We have been made aware of some recent technology in the application of pulsed low-power (<1kW) laser sources with pulsed single wire and multi-wire GMAW. This laser GMAW hybrid technology has been explored preliminarily and currently at the DOE labs and university levels, however there is no U.S.-based developmental system to serve as the development platform for the technology. Through this opportunity we would develop the system for such development, and work to provide the specifications and process information for a commercial test bed. AMET is currently the major U.S.-based company providing the automated welding systems used for wind tower fabrication. As such, we have immediate knowledge and U.S. customer base supporting the industry that would benefit from commercialization of the technology that is being studied. A system such as we are discussing would be priced similarly to current technology but have significantly higher throughput and much more efficient use and lower inherent energy consumption for welding in operations such as wind tower fabrication.
7. **Project Deliverables:** Establish an automated hybrid LAW/GMAW weld cell with capabilities to complete evaluation of welding process variables. This system would include pulsed laser process head, GMAW welding system employing new generation digital inverter based welding supply and AMET XM Weld Process Controls for a modular, multi-process welding system capable of digital communication with other industrial machines to create a highly integrated and flexible welding cell. Equip the system with data collection and digital controls technology suitable for industrial environment at a later date.

Complete preliminary specification development for next generation weld system and controls for hybrid LAW/GMAW commercial platform.

Investigate the technology and determine better model for low energy pulsed laser and pulsed GMAW technical mechanism, possibly with FCAW-G and/ or FCAW-S wire.

Verify and confirm expected process savings, such as increase in weld deposition rate, characterization of weld quality, demonstration of improved process stability and associated

performance improvements, greater than 50% improvement in energy usage and capture the overall fabrication efficiency and cost benefits.

- 8. Anticipated Benefits:** Preliminary studies of lower optimized techniques indicate 35% improvement in fabrication efficiency. Based on early results the equipment costs for systems will be less than current SAW approaches and will achieve significant energy and operating cost savings. It is felt that satisfactory weld properties can be achieved to meet mechanical specifications and Charpy impact results. There is strong indication that this system will achieve improved arc control, and improved process robustness, allowing for better out-of-position welding and operation in more extreme fabrication environments.

Joining of medium to heavy thickness plate structures is a major manufacturing operation in the U.S. manufacturing base. A significant change in through put and quality would be welcomed in fabrication of many parts employing plate and tank construction for both commercial and national defense industries. In this specific funding opportunity it is known that the growth rate for wind tower production required to achieve the roadmap goal of 20% by 2030 would require exponential capacity increase, it is not likely that sufficient capital can be raised to support making these towers if the facilities do not see exponentially higher through put and efficiency of manufacturing costs. A significant change such as this to the welding process would greatly enhance likelihood and improve investment risks furthering the advance of wind energy and improving U.S. manufacturing capabilities in the world markets. One of the applications currently under review has direct application in commercial and government nuclear vessels and device areas. The significance of using low-power laser for enhancing plasma energy transfer for a wide variety of fabricating applications could be an extremely significant cost and process-enabling breakthrough.

- 9. Potential Collaborating Companies:** It is very likely that any work in this area would include IPG Photonics and Lincoln Electric as collaborating companies.

Project Idea #2

1. **Project Title:** Long Service Life, Reliable Composite Wind Turbine Blades
2. **Date:** March 31, 2010
3. **Submitted by:** Pacific Engineering Inc., 1074 Saltillo Avenue, Roca, NE 68430, (402) 421-3999
4. **Approximate Start Date and Duration:** June 2010 for 12 months
5. **Statement of Problem:** The U.S. Wind Industry base does not have enough manufacturers of wind turbine blades with U.S. manufacturing facilities. Current over 70% of wind turbine blades are imported from Europe, Mexico or China and Brazil. Several OEM have built factories for large utility scale wind mill blades. However, we need to create jobs and facilities in the U.S. manufacturing sector of the growing mid-size wind industry base.
6. **Proposed Solution:** PEI and MSI have teamed up and will focus our production and fabrication on the development and commercialization of mid-size wind turbines blades (60 to 80 feet lengths) for turbines with a capacity ratings of 250kW, 600kW, and 750kW, utilizing Vacuum-Assisted Resin Transfer Molding (VARTM) Process as our key fabrication method. This will enable PEI/MSI to fill the lack of blade manufacturing capabilities in the U.S., as reported by the U.S. Mid-Size Wind Turbine Development workshop held on November 6, 2009. Our team will create a design and performance model for a mid-size, (250kW, 600kW, or 750kW) turbine blade to improve its reliability and service life. In addition, the team will design and fabricate molds and tooling to build composite blades and expand our Lincoln, NE production facilities. Our strengths consist of aerodynamic, structural, composite materials design and production engineers and computational modeling experts to incorporate lighter high strength materials (carbon fibers, high strength core materials, and improved resins) in turbine blade design, and develop analytical performance predictive models.
 - Collaborate between University experts and centers with composite manufacturing experts in order to improve wind turbine blade performance and reduce blade operating and maintenance costs through improved reliability.
 - We will utilize our University partners R&D efforts to investigate lightweight, high strength cores, pre-pegs, carbon fiber and adhesive materials that will lower the cost, and increase reliability and develop a 20-year service life of wind turbine blades.
 - Using innovative automation processes, we propose using filament winding, a center structural tube, bonding the stiffener, outer profile and the fabricating final outer skin layer using controlled filament wind patterns.
 - We will research a design based on using stiffening spar, wet attached to the center tube, or by using a film adhesive, which controls bond line and ensures continuous bond of the inner spar.
 - Investigate filament winding the outer skin by using computer generated wind patterns to place the fiber in the proper orientation on the blade outer skin.
 - Research composite materials, and turbine and blade designs, to redesign current blade specifications.

Our goal is to design turbines and blades to produce higher power outputs under low wind speed conditions, vice lower power outputs currently produced and develop techniques that will lower the cost, increase, improve reliability and increase their service life.

7. Project Deliverables: Not specified.

8. Anticipated Benefits:

- Blade and turbine interface specifications from major OEM, such as, GE Energy, Clipper Power and Data to improve current blade capabilities to convert the lowest winds to produce higher power.
- Generate and employ a skilled workforce to supply the growing renewable energy industry.
- Collaborate with industry to improve wind turbine blade performance to manufacture blades that interface with current mid-size turbines (Franklin Wind Energy Group and Ener Tech Wind).
- Reduce blade operating and maintenance costs through improved reliability.

9. Potential Collaborating Companies:

Mentis Sciences Inc., Manchester, NH
EnerTech, Kansas City, KS
University of Nebraska, Lincoln, NE
North Carolina A&T, Greensboro, NC
Florida State University, Tallahassee, FL

Project Idea #3

1. **Project Title:** Hybrid Laser Arc Welding (HLAW) for Manufacture of Wind Towers
2. **Date:** March 31, 2010
3. **Submitted by:** GE Global Research, One Research Circle, Niskayuna, NY 12309;
POC: Dr. Magdi N. Azer, azer@research.ge.com
4. **Approximate Start Date and Duration:** October 1, 2010 for 12 months
5. **Statement of Problem:** Two of the continuing barriers to greater penetration of alternative energy in the United States are the CAPEX required to install new factories and the technology development to reduce the cost of manufacturing alternative energy systems themselves. The need for advanced manufacturing processes that can bring down the cost per unit is essential to be considered a viable alternative to coal. This is also essential in establishing U.S. as a leader in the alternative energy sector, thereby creating manufacturing jobs. For example, in its report, 20% wind by 2030, the Department of Energy noted the following:

“One wind blade manufacturer with significant international manufacturing experience estimates that, to make a U.S. factory competitive, the labor hours per blade would need to be reduced by a factor of 30% to 35%. To ensure that the bulk of these manufacturing jobs in the United States, automation and productivity gains through the development of advanced manufacturing technology are needed. These gains will allow the higher U.S. wage rates to be competitive.”

To reduce the cost of alternative energy manufacturing, and thereby increase U.S. competitiveness globally, advanced manufacturing technology will be required.
6. **Proposed Solution:** North American wind tower fabrication for GE accounts for greater than 120,000 manhours of welding annually. One way to reduce manufacturing costs for wind towers is to utilize Hybrid Laser Arc Welding (HLAW). HLAW has the potential enhance productivity while reducing energy consumption to offset the foreign low-cost labor advantage and enhance U.S. competitiveness. HLAW technology combines laser welding and arc welding to produce an energy efficient, high productivity, welding process for heavy manufacturing. This process leverages the ability of laser to produce deep weld penetration and the ability of gas metal arc welding (GMAW) to deposit filler material, thereby producing stable, high quality, welds on joints with gaps and mismatches typical of those seen in heavy manufacturing.
7. **Project Deliverables:** Over the last 18 months, GE Global Research (GEGR) has developed a HLAW facility that is unique in North America. This system consists of a 20kW fiber laser, which is the only facility in North America that has a 20kW laser. With this equipment, GEGR has demonstrated the capability to weld wind tower structural steel in thicknesses between 11mm and 22mm.

These thicknesses are typical of the thicknesses seen in the 80m towers that support a 1.5MW wind turbine. In addition, GEGR has conducted experiments to evaluate the capability of the technology to handle gaps typically seen in tower manufacturing. Based on this work, which has been conducted on a lab setting, GEGR intends to utilize this funding to transition the

technology developed in the lab (MRL 4) to one of GE's wind tower manufacturers. In this role, GEGR and the tower vendor will evaluate the following topics.

- Prepare a risk abatement plan for implementing HLAW in a manufacturing environment.
- Develop a welding system capable of operating in a tower-manufacturing environment.
- Demonstrate the ability to weld tower steels with adequate quality to handle the gaps and mismatch seen in typical production.

What makes all of this unique is that it would be the first application of HLAW for tower welding. Furthermore, the specific deliverables are as follows:

- List of barriers that would prevent installation into a tower manufacturer's shop.
- Bill of materials proposing what equipment is required to weld wind towers.
- Cost-model validating cost benefit of the HLAW process.

- 8. Anticipated Benefits:** As a productivity enhancing technology, HLAW processing at GE will have an impact in retaining domestic jobs by making domestic manufacturing more competitive with low-cost foreign fabrication facilities. By moving from traditional joining technologies to HLAW could reduce joining energy requirements from 10 kWh/ft to approximately 0.9 kWh/ft of material joined down for some joint configurations, a reduction of up to 90%. With full penetration into all North American GE tower suppliers and at a production volume of 3,000 unit/year, this could save more than 260 thousand kWh annually. This would be more than 1,200 thousand kWh annually when the U.S. reaches its full capacity of 17,000 towers per year which is needed to achieve 20% wind penetration by 2030. Utilizing this same technology, GE sees application in welding of gas turbine components, welding of pipeline for the oil and gas industry, shipbuilding, and plane manufacturing. This is significant because in 2000, U.S. heavy manufacturing industry spent more than \$220M on energy for thick section welding. With 50% industry penetration, the 90% reduction in energy consumption available through HLAW processing could amount to an annual U.S. energy savings of approximately 1.1 billion kWh. Beyond energy savings, the cost savings is estimated to be \$8,000/tower.
- 9. Potential Collaborating Companies:** Because GE does not produce its own towers, a critical aspect of this program will be partnering with one of GE's tower suppliers to test and implement this technology into GE's supply chain. These tower vendors exist across the United States.

Project Idea #4

1. **Project Title:** CAD-Driven Rapid Digital Tooling Application for Manufacturing of Composite Wind Blade Shapes
2. **Date:** March 31, 2010
3. **Submitted by:** Spatial Integrated Systems, Inc., 2815 Rouse Road Extension, Kinston, NC 28504; POC: Dr. Ali Farsaie
4. **Approximate Start Date and Duration:** June 2010 for 12 months
5. **Statement of Problem:** Conventional tooling used in manufacturing composite wind blades involves a lengthy and costly process. If the tooling is made from metallic materials, the final tool shape is usually machined using a CNC process, often from a solid block of metal. Although metal tools are rigid, strong and durable; the time and cost of programming and machining required negatively affect the cost per unit and the cycle time required to produce the first article. Additionally, conventional tooling is heavy, potentially difficult to transport, and vulnerable to CTE issues. Mitigating these disadvantages, composite tooling is lightweight for comparable strength and far less vulnerable to CTE mismatches. However, composite tooling fabrication typically requires a multi-step process which could involve labor-intensive layup and its durability depends on its damage tolerance; thus presenting an opportunity for improvement in the tool fabrication process.
6. **Proposed Solution:** With its coastline, Outer Banks and mountain regions, North Carolina has outstanding wind resources offering tremendous opportunities for developing wind power on the land as well as offshore. Wind power is an attractive option for utilities, alternative energy businesses and entrepreneurs in North Carolina looking to produce clean electricity from renewable sources. The U.S. market for wind turbines is expected to reach \$61.0B by 2013 up from \$7.9B in 2007. North Carolina stands to gain from this spurt in growth. According to a study by National Renewable Energy Laboratory (NREL), the Atlantic coast could be home to more than 1 Gigawatt of offshore wind farms. NREL has pegged the potential at roughly 900 megawatts off the Pacific coast. SIS, working closely with North Carolina's Eastern Region (NCER), has access to a network of companies that are involved in development, manufacturing and installation of wind turbines. SIS has been a long time member of NCMS and was able to attract seven maintenance depots to its NCMS project, OptiCAM. SIS is fortunate to be neighbor to one of the largest world aircraft composite manufacturers, Spirit Aerosystems. With the presence of composite manufacturers and research organization, SIS will have exposure to state-of-the-art advanced composite materials, technologies and tooling. This proposal will study the benefits of manufacturing a typical composite wind blade shape segment using digitally manufactured tooling directly derived from CAD versus the traditional tooling methods to manufacture composite wind blades. A model for digitally manufactured tooling will be created from the 3D CAD model of the wind blade shape. Tool material selection and tool design will consider factors such as rigidity, heat deflection of the tool and the heat transfer through the tool and CTE. Objectives of this project are to create two tools:
 - i. One tool will be made using the rapid tooling derived from the CAD model requiring little or no machining.

- ii. Another tool to be made using a metallic material machined from the CAD model.

Composite parts will be fabricated using vacuum-bagged composite layup requiring cure temperatures of not more than 250°F. Both parts will be fabricated using the same layup scheme and cured per material manufacturer specifications. Technology is also available to monitor the true-state viscoelastic material properties during the cure cycle and it may possibly be utilized in this project to compare the cure characteristics of these two tooling scenarios, shedding light on more potential benefits. Potential also exists for alternative curing techniques with digitally manufactured tooling materials.

7. Project Deliverables:

Demonstration of rapid (digitally manufactured) tooling technology – as compared to traditional tooling techniques – for use in making first-article fabrication or small-batch manufacturing of a composite wind blade shapes.

Measurable deliverables include reduction in tool fabrication time, reduction in tooling costs, reduction in manufacturing costs per part, reduction in tooling weight, and cure times. Other significant but not as readily quantifiable deliverables, include streamlining of the tooling process, ability to integrate physical features in the design of the digital definition of the tool.

However, these deliverables can be quantified in a specific production environment.

8. Anticipated Benefits:

Using the proposed rapid digital tooling technology method, there would be no need to produce a master model, and then make interim tooling from that model before deriving a final production tool. Also, the need to perform elaborate multi-axis machining, often on hard-to machine materials, will be reduced and perhaps eliminated. This will ultimately save not only tool design and fabrication costs, but also will affect the throughput in terms of faster first article manufacturing. Other potential benefits include: faster cure times resulting from better heat transfer through innovative tool design, the ability to incorporate thermocouples at the tool-ply interface, the ability to integrate and fabricate features in a digitally manufactured tooling which would not be feasible or affordable otherwise.

Rapid prototyping including rapid tooling has been around for many years. The rapid digitally manufactured tooling concept described in this project can be applied to many industries involving composite fabrication – and even some non-composite fabrication – which requires a tool or mold, whether it be renewable energy such as wind power; or widespread fabrication needs across many industries, including aerospace, defense, marine, automotive, transportation, construction, recreation and others.

Potential benefits to the U.S. manufacturing base of rapid digital tooling technology are very promising and profound due to the scope for its application across the wide-ranging spectrum of industries as mentioned above.

Proposed project not only impacts wind blade industry but also broader composites manufacturing industry and hence can help create more jobs in Eastern NC, not only in manufacturing industry but also in energy sector.

- 9. Potential Collaborating Companies:** SIS is discussing this proposed project with several companies within NC and outside the state.

Project Idea #5

1. **Project Title:** Wind Turbine Blade Fabrication Automation
2. **Date:** March 31, 2010
3. **Submitted by:** Ashland Performance Materials, 5200 Blazer parkway, Dublin, OH 43017;
POC: Cedric Ball, caball@ashland.com, (614) 790-4161
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** Wind turbine blades are typically fabricated from epoxy or unsaturated polyester resins, glass fiber reinforcements, and balsa cores. While these materials are relatively inexpensive, the fabrication incorporating them is a highly labor-intensive process. The high labor content limits the ability to control total blade production costs as labor costs escalate, and forces manufacturers to locate facilities in areas of the world with low labor costs. These areas are often far from growing wind markets, requiring incurrence of extensive transportation and logistical expenses. These materials also require extensive processing times.

The highest labor content in blade fabrication is the manual placement of glass fiber, usually in the form of woven mat or cloth fabrics. This is followed by bagging of the blade, installation of the resin distribution system, and finally core placement. A high degree of labor is also required to produce kits of both glass fiber and core material. Alternative raw materials and form factors are required to automate the fabrication process – reducing costs and improving part quality.

6. **Proposed Solution:** Significant advances in composite fabrication have been realized in other industries and components, namely aerospace and transportation. It is well understood what materials, form factors and product design characteristics best lend themselves to automated composite fabrication. The project team proposes to use knowledge gained in prior work and apply it to composite fabrication of wind turbine blades. We will evaluate the automated placement of high performance glass fibers that provide equal structural properties at reduced weights. Fiber preforming has been successfully demonstrated for high volume production of large composite parts with complex geometries. Robotic systems allow for precise fiber orientation, reduced scrap and material waste. The team will evaluate and test this technique for producing wind turbine blades.

The project team will develop a new blade design that incorporates materials that are more conducive to automated fabrication and reduce production cycle times. An automated fabrication method will be developed to produce blades at higher and more consistent quality levels. Laminate panels will be designed, fabricated and tested against conventional blade sections. Finite element analysis will be conducted on a full-scale blade design. This project will demonstrate the feasibility of automated glass fiber placement to produce a blade of equal or greater performance to current designs. Pending project success, a follow-on project will be conducted to fabricate and test full-scale prototype turbine blades.

The project team has extensive experience developing composite part design and fabrication methods for both aircraft and automotive components. The team possesses the ability to fabricate laminates using automated equipment and perform all the required testing.

7. Project Deliverables:

- Identify composite reinforcements, resins, tackifiers and form factors that are conducive to automatic placement.
- Laminate sections, representing typical turbine blade sections, will be prepared using automated techniques.
- Test results from physical testing of the prepared laminate and comparison to conventional blade structures.
- Design for full-scale blade, materials of construction and associated form factors, and the fabrication process. The blade will have a performance level comparable to existing turbine blades, at a minimum, and projected lower fabrication costs.
- Final report outlining blade design, fabrication process, and projected costs.

8. Anticipated Benefits:

- Turbine blade design that is more amenable to automated composite fabrication methods.
- The materials and fabrication techniques will leverage prior composite materials development in the aerospace and transportation industries.
- Pending project success, the project team will seek funding to build and test a full-scale wind turbine blade set using the automated fabrication process.
- Successful development of this technology will reduce the cost of wind turbine blade production by 10-15%. Reducing the fabrication labor content will reduce cycle times and improve blade quality, uniformity and reliability.
- More turbine blade fabrication will be done in the U.S. where the wind market is experiencing substantial growth.
- Blade designs incorporating alternative materials and designs will enable lighter weight and improved airfoil complexity.

9. Potential Collaborating Companies:

MAG
Molded Fiber Glass (MFG)
Owens Corning
WebCore Technologies
University of Dayton Research Institute
National Composites Center
Edison Materials Technology Center (EMTEC)

Project Idea #6

1. **Project Title:** Utilization of Carbon in Wind Turbine Blades Manufacturing Using the “Fibramatic” Technology
2. **Date:** March 31, 2010
3. **Submitted by:** Gamesa Wind US, 2050 Cabot Blvd., Langhorne, PA 19047;
POC: Unai Ocaña, uocana@gamesacorp.com, (215) 710-3100 ext. 28316; (267) 934-5545
4. **Approximate Start Date and Duration:** May 2010 to December 2010
5. **Statement of Problem:** Gamesa is considering designing and manufacturing larger blades using its “Fibramatic” technology (fully automated manufacturing process, including the lamination of dry fiber). Current technology has been developed for glass fiber only, but due to limitations in weight and loads, carbon will be a better candidate. Center for Composite Materials (CCM) of University of Delaware will collaborate with Gamesa in determining the optimal process to introduce carbon laminates in the fully automated process.
6. **Proposed Solution:** CCM of University of Delaware will collaborate with Gamesa with two clear objectives:
 - Identification of the optimal process to introduce carbon in blades manufactured by Fibramatic process.
 - Use of LIMS (Materials flow modeling software) to simulate the infusion of hybrid (glass + carbon) laminates with the selected technology.
7. **Project Deliverables:**

Phase 1 – Selection of Optimal Process for carbon in “Fibramatic”

- Study containing a comparison of the alternatives (CCM + Gamesa).
- List of parameters needed to perform the simulations (CCM).
- Report of simulation results including infusion strategies, curing cycles, expected springback, and expected mechanical properties (CCM + Gamesa).
- Checklist for the manufacturing of specimens (CCM).
- Suggestions on mechanical and process tests to be performed.
- Report on reliability of LIMS to simulate (comparison with experimental results) (CCM).

Phase 2 – Full-Scale Simulation Using LIMS

- List of additional parameters needed to perform the full-scale simulations (CCM).
- Report of simulation results including infusion strategies, curing cycles, expected springback, and expected mechanical properties (CCM + Gamesa).

8. Anticipated Benefits:

- The impact of the project will be the expansion of automation possibilities by the incorporation of carbon-glass hybrid fibers. This will allow the fabrication of large blades (more than 50 meters). Automatic tape layers placement technologies like Fibrumatic reduce labor costs while increasing reliability and quality.
- As the concept of automatic placement of hybrid glass-carbon layers will be demonstrated, CCM of University of Delaware will benefit. Equipment fabricators such as M. Torres could further incorporate it on their developments. Patents created could be licensed to other industries such as construction and transportation.
- Gamesa will pursue the manufacturing of larger blades with this technology for new turbine models in the U.S. including in-house and subcontracted manufacturing.

9. Potential Collaborating Companies:

CCM University of Delaware
M. Torres

Project Idea #7

1. **Project Title:** A Cellular Carrier Composite Molding Process (C³M) for Molding Composite Wind Blades
2. **Date:** March 31, 2010
3. **Submitted by:** Global Composite Solutions, 100 W. Big Beaver Road, Suite #200, Troy, MI 48084; POC: Carmen Franko (business issues) cfranko@globaltech.us, Nippani Rao (technical issues) nrao@globaltech.us, (313) 982-1435
4. **Approximate Start Date and Duration:** September 2010 for 6 months
5. **Statement of Problem:** Current molding process (RTM) for wind blades is not fast enough for the high volume production needed to bring down the cost required for broad acceptance of the technology.
6. **Proposed Solution:** C³M is a fast cycle manufacturing process that will reduce the cost of blade production. A flexible urethane foam is saturated with the appropriate amount of Vinyl Ester resin; fiberglass reinforcements are added to the saturated foam on both sides and placed in a heated (250°F) compression molding tool. About 100 psi pressure is then applied to cure the part. About two (2) minutes is adequate to cure a composite which is 2-3mm thick. The resin flows from the foam vertically into the reinforcements and the compressed flexible foam remains in the center of the composite, providing an I-beam effect on stiffness properties.

Objectives:

- Provide a fast cycle process capable of 30 blades per hour compared to an RTM type process with cycle times in the range of 8-12min (5 to 7.5 blades per hour.)
- Improve structural integrity by 20-30%, through optimized cast metal core (aluminum or magnesium) and the foamed core surface.
- Reduce scrap levels by 10% through a more efficient C³M process.
- Reduce volatiles by 50% because of a closed mold compression molding C³M process.

7. Project Deliverables:

- Technological advancement of the concept includes a wind blade with a metal (aluminum or magnesium) reinforcement for structural integrity, a rigid urethane foam core over the metal reinforcement for aerodynamic surface definition and a 2-3mm fiberglass/vinyl ester skin (C³M composite) for durability. The shape of the metal reinforcement (length x width x thickness) will depend on the structural requirements. The shape(multi curvature) of the self skinning foam core will depend on the aerodynamic requirements.
- The C³M composite will provide the environmental durability of the wind blade. The resin flow in the C³M process is vertical and allows a faster flow of resin from the flexible foam reservoir (carrier) into the fiberglass fabric reinforcements. A vinyl ester resin systems can be catalyzed to cure in 2min. per Ashland Chemical.

- Demonstration of our C³M process in molding a lighter weight, stiffer composite over a conventional RTM composite. Lighter weight and stiffness comes from the flexible urethane foam carrier acting as an I-beam in the center of the cured composite.
- A prototype part will be delivered. Size to be determined.
- A mathematical model for predicting the mechanical properties.
- A CAD/CAE study to optimize and verify structural performance.

8. Anticipated Benefits:

- Lower manufacturing costs due to faster cycle times 2min for C³M vs. 10min for RTM (5 times higher productivity).
- Higher mechanical properties of the C³M composite vs. RTM composite due to I-beam effect from the C³M process (about 20% higher).
- Lighter weight compared to an RTM composite (15-20% lower density) due to lightweight compressed flexible foam carrier, inherent to the C³M process.
- Environmentally more desirable materials. Plan to use a polyol produced from scraped flexible foam in the rigid foam (up to 60% recycled content).
- Reduction in the cost of wind energy to society overall.

9. Potential Collaborating Companies:

MSU Composite Structural Center for structural design and testing
Haddock Composite Co. for molding
Excel prototype tooling company for tools
Infichem Polymers LLC, Polyol from scrap urethane for rigid urethane core
Ashland Chemical for Vinylester resin
Owens Corning for fiber glass reinforcements
Unique Fabricating Inc. for Flexible foam core carrier
Merginc. Materials Engineering Resource Group for casting technology of aluminum and magnesium

Project Idea #8

1. **Project Title:** Advanced Manufacturing Technologies for Wind Blade Manufacturing of Horizontal and Vertical Axis Wind Turbines . . . New Designs/New Materials
2. **Date:** March 31, 2010
3. **Submitted by:** LightWeightStrategies LLC, 25800 Romany Way, Franklin, MI 48025;
POC: Dr. Gerald S. Cole, geraldscole@att.net, (248) 626-3232, cell (248) 408-1408
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** The proposed project is associated with designing and manufacturing turbine blades for both low power (1-5kW) small (<5m long) vertical axis wind turbines (VAWT's) for small business and residential use, as well as for the large (>1MW) horizontal axis wind turbines (HAWT's) which have 25-40m long rotors.

VAWT's are smaller and are more efficient than HAWT at low wind speeds and where winds blow omnidirectionally. But for steady directional flow, HAWT's are much more efficient and produce more kW.

Large blade design/manufacturing capability and mounting systems are based primarily on polymer-glass composites. 2010 global volumes are about 200,000 blades pa, and a blade for a typical 1.5MW turbine weighs ~ 5T at a typical cost of \$120,000. But they suffer from environmental degradation. In this project we will produce lower cost and lighter weight VAWT and HAWT rotor blades using aluminum. Normally, blades made from aluminum have suffered from excessive weight and low fatigue life, because of their extrusion manufacturing process. In this project we will investigate using superplastic forming that have no internal stresses to form high strength thin (1-2mm) aluminum blades. Such blades will be less prone to fatigue failures and lighter than current extruded alloy. And because of the large elongations can be formed into more complex shapes. Like aircraft wings, they are not prone to environmental failure. In order to reduce joining stresses, the blades will be friction stir welded and adhesively bonded.

6. **Proposed Solution:** Ultra-light metal blades will be designed to efficiently capture wind energy. General Motor Company's Advanced Manufacturing Technology (AMT) facility in South Lyon, MI, produces unique automotive body designs in aluminum and magnesium alloys employing a low-cost variant of superplastic forming, termed Quick Plastic Forming (QPF). But there are other companies which can also produce low-cost superplastic formed aluminum, if GM decides not to participate. QPF will be used to produce low-cost ultralight airfoils specifically designed to capture as much wind energy as possible. These will be assembled into complete blades using adhesives and coatings developed by DCT. Internal stiffness will be enhanced with conventional aircraft manufacturing techniques using foams, honeycombs and struts. In addition, glass microballoons from recycled fly ash will be examined as a very low weight reinforcement.

Negotiate with the GM AMT plant to manufacture foils and assemble them into the small blades required for VAWT's. For the HAWT's form the required 2m sections and join them into a 20m blade using friction stir welding and adhesives to produce a strong, fatigue-free bond, as with the Jaguar aluminum vehicle.

Perform testing to ensure the optimized efficiency and suitability of the modeled blade designs and manufacturing protocol for producing superplastic aluminum, and perhaps even lighter magnesium.

7. Project Deliverables:

- Model the load carrying requirements for a thin supported aluminum blade and develop designs that work for HAWT as well as VAWT to maximize load-carrying capability, minimize weight and reduce cost.
- Use Quick Plastic Forming to produce aluminum and magnesium air foils rotor blades that, because of their low weight and unique design, will more efficiently capture wind energy at lower velocity than heavier composites for HA and VAWT's. Use recycled fly ash, foams, honeycombs or local carbon fiber mats to enhance stiffness where required by the computer modeling.
- Assemble air foils into turbine blades for HAWT and VAWT designs.
- If magnesium blades are tested as possible, develop and apply coatings to enhance their durability.
- Develop a process cost model and cost per kW of generating power using aluminum vs. current designs.

8. Anticipated Benefits: QPF allows low-cost, long, highly curved, stiff designs of thin aluminum and magnesium air foils which can be stretched to almost 500% during processing. Current manufacturing is via conventional hand layup of polymer composite or thick aluminum extruded sheet. Both processes are limited in their ability to produce durable blades. Conventional aluminum and magnesium extruded sheets are heavy and tend to fatigue at the high load in HAWT's. There is no experience in VAWT.

Metal blades for wind turbines will be designed/manufactured to produce curved shapes that can "grab" air most efficiently. Blades currently are produced from polymer composites and/or carbon fibers. They are expensive, have poor durability, and can fatigue crack during service thereby reducing power output. Current metal extrusion puts microvoids in the metal that can lead to fatigue. QPF produces a stress-free part. We propose to expand the HAWT experience to VAWT. While no designs use magnesium, the team has metallurgical and corrosion expertise that could make ultra-light blades.

The large-scale production and use of HAWT's and personal VAWT's could create a new manufacturing industry for the U.S. using light metals to produce low-cost, more efficient wind-collecting blades.

9. Potential Collaborating Companies: HAWT Company such as GE Turbines, VAWT Company, aluminum producer, tbd.

Vertical Axis Wind Turbine Designs

Project Idea #9

1. **Project Title:** Hybrid Laser-GMA Welding of Wind Towers
2. **Date:** March 30, 2010
3. **Submitted by:** Applied Research Laboratory, Penn State University, PO Box 30, State College, PA 16804-0030; POC: Edward W. Reutzel, ewr101@psu.edu, and Shawn M. Kelly, (814) 863-9891
4. **Approximate Start Date and Duration:** August 2010 to February 2012
5. **Statement of Problem:** Joining of wind tower rings (or cans) and tower segments is normally accomplished through conventional submerged arc welding processes, and is a costly and time consuming barrier in realizing affordable wind power. The structural steel plates can be up to 60mm thick or more, necessitating a joint design able to accommodate the submerged arc welding (SAW) process. The wide double-side bevel joint required by this welding process necessitates the need for multiple weld passes, leading to numerous detrimental consequences including high cost of wire and flux consumables, long weld time due to low travel speeds, many opportunities for defects due to repeated starts/stops, and downstream rework caused by distortion associated with high heat input. An improved joining process that significantly decreases manufacturing time and cost while mitigating these other issues is strongly desired.
6. **Proposed Solution:** The objective is to develop tandem SAW and hybrid laser-arc welding process parameters and joint designs suitable for use in wind towers. The team will then demonstrate a locally enclosed hybrid welding system to execute such welds safely in a production setting. The outcome of the effort will be a technology demonstration of joining of parts representative of wind tower ring (can) and segment that reduces welding time by at least 80%. Hybrid welding is a process whereby a high power laser weld is combined with an arc welding process, such as Gas Metal Arc Welding (GMAW), to provide the benefits of both. The laser provides deep penetration while the GMAW process provides filler material to fill gaps and provide weld joint strength. This process was successfully demonstrated by ARL Penn State for welding steel pipe with 12.7mm thickness at GD NASSCO Shipyard, the first hybrid welding process approved by the American Bureau of Shipping (ABS) in the U.S. A portable hybrid welding system has been successfully demonstrated by ARL Penn State on a production shop floor at GD Bath Iron Works Shipyard, the first such system in a U.S. shipyard. Hybrid welding technology is already in production use for shipbuilding in Europe. The technology advancement that will be undertaken during this effort is the development of tandem SAW – hybrid weld processes and joint designs to enable greater than 80% reduction in the time required to produce wind tower rings and segments. The leading SAW torch on the Lincoln tandem SAW system will be replaced with a laser-arc hybrid process. The hybrid will provide (i) deep penetration to enable thicker lands, and (ii) filler material to fill gaps in order to prevent flux/weld blow-thru. Though this process will result in a beneficial decrease in distortion, the most significant monetary savings are expected from the fact that a thicker land will lead to much smaller beveled areas to fill, i.e., many times fewer weld passes will be required. This project will seek to develop and optimize the tandem SAW-hybrid welding process for plate thicknesses of interest to Gamesa and others in the wind industry. Impact of changes in joint designs,

laser/GMAW/SAW parameters, and laser oscillation characteristics will all be investigated. A prototype system will be designed, built, and demonstrated. Results will be fed into a detailed cost benefit analysis. Lessons learned can be leveraged in the future for offshore wind monopoles that require joining of plates with thickness >75mm. ARL Penn State will work with Gamesa engineers to define the potential operating space (material and wall thickness, realistic gap tolerance, etc.), and to develop a suitable test plan. Gamesa will provide material for testing. ARL Penn State engineers and a Penn State University graduate student will collaborate with Lincoln Electric in order to develop suitable welding parameters for incorporating a hybrid laser-arc welding process (using ARL's 12kW IPG fiber laser) to Lincoln Electric's tandem SAW system for both the initial land weld and subsequent filler welds (if required). ARL Penn State will design and integrate the hybrid welding system laser-safe enclosure. Guidance from collaborators will help ARL Penn State to incorporate lessons learned into a realistic cost benefit analysis.

7. Project Deliverables:

- Joint designs and processes suitable for tandem SAW hybrid laser welding of towers (materials and thicknesses), including test plan and test results.
- Demonstration of locally enclosed hybrid welding system suitable to produce such welds in a production environment.
- Specifications for such a system.
- Detailed cost benefit analysis.

8. Anticipated Benefits:

- Based on previous hybrid welding efforts by ARL Penn State for the U.S. Navy and Shipbuilding Industry, it is anticipated that time savings for joining of wind tower cans and segments will be greater than 80%.
- Additional savings will be realized through reductions in (i) consumables, (ii) opportunities for defects, and (iii) downstream rework.
- Close collaboration between the partners will ensure that the technology is directly transferred to both welding equipment suppliers and wind industry end users.
- Training of a graduate level engineering student will help to both (i) provide skilled, experienced personnel and (ii) transition the technology to the U.S. wind industry.
- Lessons learned will be transferred to other equipment suppliers and end users through presentation of results in at least one wind industry conference or publication.

9. Potential Collaborating Companies: No additional collaborating companies are envisioned at this time.

Project Idea #10

1. **Project Title:** Laser Welded Wind Turbine Blades
2. **Date:** March 31, 2010
3. **Submitted by:** Applied Research Laboratory, Penn State University, PO Box 30, State College, PA 16804-0030; POC: Edward W. Reutzel, ewr101@psu.edu, and Shawn M. Kelly, (814) 863-9891
4. **Approximate Start Date and Duration:** August 2010 to February 2012
5. **Statement of Problem:** The cost of wind turbine blade fabrication, transportation, field installation, durability, and lifecycle cost are a major factor in the overall cost of wind power. Too few companies exist with the skills and expertise necessary to produce, deploy and maintain large-scale lightweight and affordable composite blades necessary for ground and off-shore turbines >2MW. New blade designs enabled by recent advances in technology are necessary to increase the pool of U.S. manufacturers that can compete in this important market, ultimately leading to a reduction in the cost of wind energy.
6. **Proposed Solution:** The objective is to assess the technical and economic feasibility of a novel blade design comprising an aluminum, laser welded airfoil structure as a potential replacement for conventional composite blades, and to educate and transfer the design and manufacturing technology to materials suppliers, fabricators, and end users. Laser system technology has experienced unprecedented advances in the past five years, in terms of both increased capability and reduced cost. The U.S. manufacturing base is just beginning to realize the expansion in the low-cost design space that this leap in laser technology has enabled. For example, ARL Penn State has recently designed and fabricated a new stiff and lightweight laser welded sandwich structure, LASCELLTM, for use as a watertight door (right). The fabrication technology has been transferred to two U.S. manufacturers, and the door is currently being evaluated by the U.S. Navy as a replacement for thousands of standard watertight doors in new ship designs. A similar design concept is envisioned for wind turbine blades. Laser welded aluminum aerospace structures are already being used in the Airbus A318 and A380 aircraft. Such a blade could be produced in sections to reduce fabrication and transportation cost and could be joined via conventional welding in the field. A preliminary paper study was conducted to compare cost and weight of such a blade to a conventional fiberglass blade. The comparison was based on a standardized blade developed by NREL under the DOE's WindPACT program in 2001. Based on this comparison, an aluminum blade with stiffness equal to the WindPACT standardized composite blade under strain limited conditions would weigh 55% of the baseline blade. Using a value of \$2 per pound of aluminum sheet, and assumptions for typical laser cutting/welding speeds and hourly costs to operate laser cutting systems, the cost of such an aluminum blade is expected to approach a mere 22% of the baseline composite blade cost. LASCELLTM and prototype improved watertight door. Numerous assumptions have gone into this preliminary review, and a more comprehensive technical assessment and cost benefit analysis is necessary before the wind industry will embrace this radical concept. The proposed program will generate the data necessary to prove technical and economic feasibility. Specifically, Penn State will work with Gamesa engineers to settle on design guidelines that will be fed into an FEA-based

optimization of the aluminum blade design conducted by Penn State. Concurrently, Penn State will collaborate with Alcoa engineers to determine optimal materials and test protocol to determine fatigue properties of applicable laser welded joints. Materials provided by Alcoa will be laser welded in ARL Penn State's state-of-the-art High Power Laser Laboratory, and then tested as required. Once complete, the optimized designs will be utilized to fabricate a quarter-scale section of aluminum blade to develop manufacturing techniques and assess actual fabrication costs. The design and lessons learned during prototype fabrication will be used to produce a significantly refined cost analysis of the proposed blade system. The FEA optimization techniques, designs, and fabrication lessons learned will be transferred to partner organizations and presented in at least one related wind industry conference or publication.

7. Project Deliverables: An optimized novel aluminum blade design concept enabled by recent advancements in high power laser technology will be developed, and a quarter-scale blade section will be fabricated, in order to generate an accurate assessment of the technical and economic feasibility. If successful, the innovative design will enable dozens of metal fabrication shops around the country to compete in this important industry. Specifically, the following will be delivered:

- Optimized blade design (by FEA).
- Evaluation of fatigue properties of applicable laser welded aluminum alloys and laser welded joint configurations.
- Quarter-scale prototype aluminum blade section.
- Refined cost benefit analysis.
- Presentation at a wind industry conference.

8. Anticipated Benefits:

- Blade costs may approach 22% of NREL WindPACT baseline composite blade costs.
- Metal blade concepts could open the wind turbine blade market up to dozens of conventional metal fabrication shops the U.S. manufacturing base around the country that cannot now compete.
- Training of a graduate level engineering student will help both to provide skilled, experienced personnel and to transition the technology to the U.S. wind industry.
- Lessons learned will be directly transferred to material suppliers and end users through interaction with collaborators, as well as through presentation in at least one wind industry conference or publication.

9. Potential Collaborating Companies: Metal fabricators with interest in laser processing and/or aluminum fabrication are encouraged to participate as observer or in helping develop a realistic cost benefit analysis.

Project Idea #11

1. **Project Title:** Optimized Carbon and Glass Fiber Reinforced Wind Turbine Spar Caps Using Continuous Reverse Pultrusion Production
2. **Date:** March 31, 2010
3. **Submitted by:** Profile Composites Inc., 2071B Malaview Avenue W, Sidney, BC, Canada V8L 5X6; POC: Geoffrey Wood, geoff.wood@profilecomposites.com, (250) 655-7142
4. **Approximate Start Date and Duration:** July 2010 to September 2011
5. **Statement of Problem:** Fabrication of carbon fiber spar caps has proven to be an expensive and time consuming operation for the wind turbine industry, compounded by the issues arising with materials placement and handling for very long blades. A desire to accelerate production rate, remove excessive labor costs, and provide consistency in quality has led several wind turbine blade manufacturers to investigate automation approaches. The primary automation approaches being considered include *tape placement* machinery and attempts to automate the dry fiber placement for *infusion*. Tape placement uses extremely expensive equipment, a very costly material form (prepreg), and still requires a vacuum/oven cure at minimum at the end of the process cycle. Dry fiber placement followed by infusion removes only one of the manual steps in the process and may save only about 30% of the labor at best.
6. **Proposed Solution:** The proposed solution is to modify the *pultrusion* method of high volume fabrication in the composites industry which is fully proven, continuous production technology. Pultrusion can be envisaged as very similar to metal extrusion except the material is now *pulled* through the die using the fibers while the resin is curing in the heated die. The idea, which we believe is completely unique, would be to setup the pultrusion system on a traveling gantry over top of a mold, and continuously produce the carbon fiber spar. The partially cured spar would be placed onto the heated mold immediately behind the traveling die and then fully cured in the final shape (with required twist and bend that regular pultrusion cannot accommodate).

Benefits seen from the *continuous reverse pultrusion* approach would be a system that naturally tensions and collimates the fibers so the spar cap unidirectional fibers are near perfectly aligned. It would also allow for near-fully automated production using the lowest cost of all input materials forms, which is carbon tow on creels direct from manufacturer and drum resins. This provides a huge benefit over the *tape placement* approaches that use prepreg which is the highest raw materials cost input, or *infusion* that uses an intermediate cost material (stitched 0.5m wide unidirectional fabric). Machinery costs are much lower than *tape placement* but greater than the dry fiber placement machinery costs being developed for *infusion*. Benefits also include being able to work with any of the major pultrusion resins, including high performance epoxies, polyurethanes, and vinylesters, leading to a widely applicable system not just limited to carbon fiber spar caps, but glass fiber blades as well.

The optimum solution would require a die with moving internal platens (to accommodate thickness changes in the spar cap which may vary from 2mm thick to 15mm or more thickness), however the proposed solution could be tested without this level of complexity in order to validate the concept, using a constant thickness die at first. The proposed budget allows for

making several large test sections at around 20 meters in length, and would require cost contribution from the prime involved (suggested GE herein) to Profile as the project lead.

7. Project Deliverables:

Capability to produce carbon fiber spar caps for wind turbine blades at any length/thickness with an automated production process.

Machine, mold, and materials system for producing continuous carbon fiber spar caps (concept demonstrator level); 20 meter long test parts; complete proof of concept and basis for entering production demonstrated to OEM.

8. Anticipated Benefits:

Raw materials input costs reduced by a factor of about 30%; labor costs reduced by almost 80% compared to today's infusion/prepreg (non-automated) manufacturing; production rate increases will be completely dependent on the rate of pulling that can be achieved, this could be anywhere from a 25% improvement to a 3-fold improvement in throughput.

Technology transfer would be directly to partner organization involved in the funding, and we would propose a common license based on the applicability and protection of the technology; the partner can then distribute the technology to their preferred suppliers for blades.

The capability to lower costs of the primary structural component of any wind turbine blade would greatly increase the competitiveness of U.S. industry, and the installed capacity base can grow rapidly with the "freed-up" labor applied within factories to the skin and root-section manufacturing which is much more difficult to automate.

9. Potential Collaborating Companies:

GE
Bayer
Toray

Project Idea #12

1. **Project Title:** Laser Guidance for Alternative Energy Systems
2. **Date:** March 31, 2010
3. **Submitted by:** Assembly Guidance, 27 Industrial Avenue, Chelmsford, MA 01824;
POC: Scott Blake, sb@assemblyguide.com, (978) 244-1166
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** Laser projection used in the production of hand laid aerospace composites has yielded documented reductions in process costs ranging from around 50% to as much as 85%. Current processes used in the production of wind turbine blades are similar to the processes used by aerospace composites manufacturers before the advent of laser projection. Use of laser projection in the production of composite wind turbine blades is inhibited by a lack of integration and process refinement. The cost of creating, refining and documenting the first laser system for wind turbine production is too great to be borne by a laser projection vendor or a turbine blade manufacturer. ("the first one costs too much, we're building blades, not developing lasers..."). For example, the final shape of a blade is critical. If the shape of the surface does not match the design shape, the blade performance is degraded. Profiling, or selectively sanding a blade surface to improve conformity to the design, is performed without accurate guidance as to where and how much to sand. This information is available on a computer screen or printout, but not where it is needed to guide the technician performing the profiling. Using rulers or large plots on mylar takes much longer than performing the sanding operation. The proposed effort (integrating laser guidance with existing metrology and surface analysis tools) will yield a complete, ready for production system that projects patterns onto blade surfaces, in a full size, paint-by-number fashion, easily cutting the total process time for profiling in half (from days to hours). Drilling blade attachment bolt holes is another process where the accurate setup consumes most of the process time, while having marginal accuracy. The large, complete blade must be accurately aligned with great precision relative to the drilling machine. The proposed effort (integrating laser guidance with existing metrology and design tools) will yield a complete, ready for production system that projects line-up references that continuously indicate where the blade needs to be in all six axes of movement, to the precision of better than 1/16".
6. **Proposed Solution:** The proposed effort develops data and user interfaces for the Assembly Guidance LASERGUIDE system for use in process development at blade manufacturing facilities, in (but not limited to) blade profiling and blade alignment for drilling. The integrated system will use blade facility's design data and laser tracker. The objectives are to deliver a complete, integrated Design Model/Metrology Software and Tracker/Laser Projector System that:
 - Reduces process times for blade profiling and blade alignment for drilling by >75% with equal or improved finished process accuracy.
 - Is portable in a fashion similar to a laser tracker (one person transport and setup/setup <10min.
 - Is operable by a technician with a skill level similar to that required for the laser tracker.

7. Project Deliverables:

- All hardware and software (leased or contributed) to run production blade profiling and alignment for drilling.
- Documentation for system operation for profiling and drilling.
- Documentation for refining the system for other blade processes: repair, assembly, tool fabrications (drilling, heater wiring installation, ductwork).
- Industrial Engineering Metrics: accuracy and cycle time baseline, cost saving with integrated laser system.

8. Anticipated Benefits:

- Immediate payback with documented ROI for a production system of less than one year.
- Improvements in dimensional accuracy resulting in improved blade performance.
- Reduced rework and scrap.
- Establishment of integrated, portable laser projection as an easily implemented tool for process improvement.

9. Potential Collaborating Companies:

TPI
Vestas
GE

Project Idea #13

1. **Project Title:** Design Portal for Rapid Assessment of Wind Blade Design in Support of Advanced Manufacturing Concepts
2. **Date:** March 30, 2010
3. **Submitted by:** Alpha STAR Corporation, 5199 E. Pacific Coast Highway, Suite 410, Long Beach, CA 90804; POC: Kay Matin, kmatin@alphastarcorp.com, (562) 985-1100, ext. 30
4. **Approximate Start Date and Duration:** June 2010 to March 2011
5. **Statement of Problem:** The project goal is to enable rapid development of commercially viable designs of model-based wind turbine blades, improve their manufacturability and broaden the manufacturing base through the implementation and demonstration of a wind blade design/analysis/manufacturing cloud-based portal. This challenge involves a rather complex ecosystem comprised of supply chain manufacturing businesses, consulting firms and emerging independent software vendors all with unique capabilities, different domain interests and varying manufacturing analysis computing skill levels.

Alpha STAR Corporation (analysis software) and Nimbis Services Inc (portal hosting service) propose to demonstrate a Design Portal Concept (DPC) for rapid assessment of wind blade design concepts. The goal is to enable the rapid evaluation of new model-based wind blade commercially viable designs, improve their manufacturability and broaden the manufacturing base through the implementation and demonstration of a wind blade manufacturing analysis portal. The DPC system will provide designers and analysts with the capability to evaluate the durability and damage tolerance (D&DT) and fatigue life of wind blades made of advanced lightweight materials. The proposed system will provide a web-based capability for material selection and modeling (library of advanced polymers), finite element model generation, and identification of potential failure modes, load limits, and quantification of reliability.

Why is this capability important beyond this project? Three years of Council on Competitiveness research through its HPC Initiative (www.compete.org/hpc) shows, that while high performance computing model-based simulation is a “game-changing” technology, it remains a largely underutilized asset. The U.S. has world-class government and university HPC users, but relatively few experienced users in industry. Lack of analysis expertise, availability of easy-to-use HPC software, and access to more powerful systems is preventing the growing group of users from progressing in their use of this technology. The proposed wind turbine blade design/analysis/manufacturing portal lowers the entry barrier for this very unique wind turbine blade development paradigm.

6. **Proposed Solution:** The web-based wind blade analysis portal or Analysis as a Services (AaaS) will be accomplished by utilizing Nimbis Services existing core brokerage technology with a user supportive environment for hosting domain specific portals, developing/hosting emerging model-based simulation applications, and e-commerce distribution system. Through the *Drupal* content management system templates and plug-ins, the domain application web portal developer are able to specify a required virtual machine image along with a set of parameters and constraints for launching the back-end computing and software application services. When the domain specific portal is run, the brokerage service will allocate the virtual cluster machine

instance of the appropriate type, software applications and connect with a user selected computing cluster over a virtual private network. Nimbis computing providers are Amazon, R-Systems, IBM, and Ohio Supercomputing Center.

Alpha STAR will provide the wind turbine blade design/analysis software and documentation, define the application workflow and develop the graphical user interface to enable turbine blade design engineers and fabricators to design cost-effective wind turbine blade concepts and assess their manufacturability, installation and long-term inspection/service/repair. The capability will be inclusive of material library for tape, 2D and 3D woven and braided, carbon and glass-based composite systems. Alpha STAR is already working with Sandia on robust design of wind blades and test reduction for certification. We will provide web-based training on wind blade design to transfer material modeling and D&DT assessment technology to select manufacturers. The DPC software tools will be hosted by Nimbis Services. Nimbis will provide the e-commerce infrastructure that is necessary for a commercial realization of the wind blade analysis portal. In addition, the proposed solution is very supportive of NCMS planned regional Predictive Innovation Centers (PIC).

7. **Project Deliverables:** A Design Portal Concept for remote, cloud-based wind turbine blade design and analysis will be demonstrated. Several user wind blade concepts and manufacturing approaches will be designed with the proposed DPC at Alpha STAR, Nimbis as well as NCMS selected sites. Access to the DPC will be provided to NCMS for Beta-level evaluation.
8. **Anticipated Benefits:** The proposed DPC will significantly reduce engineering costs by minimizing design/analysis hours, software development time and computing hardware procurement. The DPC can be readily extended to other industries. Among these are the aerospace, automotive, civil engineering and consumer goods markets. The shift to cloud-based computing resources and product design/analysis software will significantly reduce the computing and IR&D costs for individual companies, allowing them to concentrate on product design and fabrication.
9. **Potential Collaborating Companies:** We will extend existing cooperation with Sandia National Laboratory and blade manufacturing partners to empower the utility of this unique wind blade analysis portal.

Project Idea #14

1. **Project Title:** Adhesive Bonding of Composite Towers
2. **Date:** March 31, 2010
3. **Submitted by:** Ershigs, 742 Marine Drive, Bellingham, WA 98227;
POC: Steve Hettick, VP Manufacturing, shettick@ershigs.com, (360) 527-3447
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** As wind turbines become larger and taller, use of steel monopole support towers becomes problematic. The size of the tower base becomes too large for transportation over public highways without incurring significant cost and logistic penalties. Substantial costs are also incurred in bringing these structures to the site and their erection requires large cranes. The size and weight of the tower can make installation in environmentally sensitive areas prohibitive. Steel towers also suffer from highly volatile materials prices. A new tower design is needed that uses less expensive materials and can be fabricated closer to the point of erection to reduce or eliminate transportation costs.
6. **Proposed Solution:** Ershigs is leading a team of highly qualified firms that are developing a composite tower design comprised of high performance resins, glass fiber, and engineered cores. These materials will be fabricated into standard components in a controlled factory environment prior to shipment to the turbine site for final assembly and erection. Size of the components is such they can be shipped via conventional means by rail or truck under normal conditions. The assembly process will incorporate a series of adhesively bonded joints – both along the length of the tower and circumferential – that will bond individual components into a complete cylinder. Cylindrical sections will be delivered to the job site for assembly into a complete tower. Ershigs proposes to evaluate various configurations for these adhesive joints as well as resin/adhesive formulations and application methods that will facilitate efficient assembly and produce joints of sufficient strength to support the composite tower loads. The joint strength will be equal to or greater than the balance of the tower wall structure. Ershigs and its team of partners have been investigating composite tower technology for over two years. They have recently won a grant from the Ohio Department of Development to further develop the concept and fabricate a full-scale 100 meter tower suitable for a utility-scale wind turbine. The Ohio project will assess the required materials (resins, reinforcement fiber, and core materials) that will produce components and completed cylinder wall sections of sufficient strength and durability. Designs of both the components and full-scale tower will be analyzed via finite elements analysis and other non-destructive means. A critical element in the onsite fabrication of the tower is joining the individual components in a manner that the joints have strength similar to the components and resultant wall sections. Adhesively bonded joints will eliminate the need for mechanical fasteners and the problems they incur.

Ershigs will explore a number of resin chemistries, application methods, and physical geometry to assess bond strengths and durability. The bonded joints must be compatible with the environmental conditions present in a wind turbine and survive for the life of the tower.

Panels fabricated in the Ohio-funded project will be adhesively bonded using materials identified in the NCMS project. These joints will then undergo both NDE analysis and performance testing under a series of load conditions. In selected cases, testing will be done to failure.

7. Project Deliverables:

- Materials will be identified and application methodology developed to produce adhesively bonded seams for use in composite wind turbine towers. The seams will have strength and bending resistance equal to or better than the tower wall section.
- Test results demonstrating joint performance.
- Final report describing the project and resultant adhesive bonding system.

8. Anticipated Benefits: A satisfactory adhesive joint will allow Ershigs to complete its development and demonstration of a 100m composite tower for wind turbines. Composite towers will allow the wind industry to continue the development of larger turbines, placed at higher hub heights, while avoiding excessive transportation and logistics costs.

Wind turbine tower costs will no longer be susceptible to fluctuations in steel prices.

9. Potential Collaborating Companies:

Ashland Performance Materials
ITW Plexus

Project Idea #15

1. **Project Title:** Automated Inspection System for Wind Turbine Blades
2. **Date:** March 31, 2010
3. **Submitted by:** University of Michigan, 1023 HH Dow, Ann Arbor, MI 48109-2136;
POC: Jun Ni and David Stephenson, junni@umich.edu, (734) 936-2918
4. **Approximate Start Date and Duration:** September 2010 for 12 months
5. **Statement of Problem:** Wind turbine blades are subject to manufacturing defects such as internal cracks and delaminations. Blades may also be damaged during transport to the installation site. It is important to identify these defects prior to blade installation to prevent costly in-service failures. Currently blades are usually inspected visually, although NDE methods based on ultrasound or thermography are being investigated. Prototype and early commercial NDE systems have long inspection cycles, cover a limited area of the blade, and require frequent manual intervention. There is a need for rapid, automated NDE methods to reliably inspect entire blades rapidly, both in the shop and at the installation site.

6. **Proposed Solution:** The objective of the proposed project is to develop a prototype automated full-blade inspection system that can be used to detect both manufacturing and transport-related defects. The system will use an ultrasonic sensor transported on a carriage outside the blade as shown in the figure above. This system will be able to rapidly scan the entire blade surface, and will be easily adapted to different blade sizes and geometries. A prototype system will be built and tested in the lab and in a field trial at a partner site.

Specific technical objectives for the development of this system are as follows:

- **Structural Analysis and Construction of a Wire-Based Axial Transportation System.** A wire system for transporting the sensor on a carriage through the blade body will be designed using structural analysis methods and constructed.
- **Design and Manufacture of the Carriage and Scanning Head.** Carriage and scanner head systems will be designed and constructed. Structural analysis, computer simulations (to determine sensor positions), and small scale tests will be used for design.

- **Development of Motion & Position Control.** A control system will be developed to position and orient sensors. Sensors will be developed and integrated into the control systems to ensure accurate positioning. Computer simulations will be used to identify optimum inspection paths.
- **Development of Data Analysis Methods.** Software will be developed to extract feature information and identify structural defects from the ultrasonic sensor net data.
- **Laboratory Validation.** Prototype hardware will be tested in the laboratory using a short composite structure simulating part of a blade.
- **Field Test at Partner Site.** The prototype system will be field tested at a partner site. In these tests results of the ultrasonic system will be compared to visual and other inspection results for blades with and without known defects.

7. Project Deliverables: The technical advance demonstrated in this project will be a novel automated NDE method for inspecting a full turbine blade within a reasonable cycle time. The deliverable of the project will be a prototype blade inspection system, validated through laboratory tests and in field tests at a partner site.

8. Anticipated Benefits: If successful, this project will permit wind turbine blade manufacturers and wind turbine installation and maintenance firms to more thoroughly inspect turbine blades at manufacture and prior to installation, reducing blade scrap and eliminating costly blade replacement.

The technology would also be useful for other composite structure applications, such as the inspection of airframe.

The technology will permit reduced costs and improve competitiveness of domestic blade manufacturers, and will also contribute toward meeting the “20% Wind Energy by 2030” initiative of the DOE.

9. Potential Collaborating Companies: AAAMBO Energy LLC

Project Idea #16

1. **Project Title:** Monitoring System for Wind Turbine Blades
2. **Date:** March 31, 2010
3. **Submitted by:** University of Michigan, 1023 HH Dow, Ann Arbor, MI 48109-2136;
POC: Jun Ni and David Stephenson, junni@umich.edu, (734) 936-2918
4. **Approximate Start Date and Duration:** September 2010 for 12 months
5. **Statement of Problem:** Reliability of wind turbine systems is a major concern for wide adoption of wind energy technology. Although the designed life expectancy for most wind turbine systems is around 20 years, actual service life is much shorter than that. Failure of a turbine blade at the base where fiberglass composite joins the metal base ring is a significant reliability issue. This critical area is subject to the full, blunt and cumulative impacts of all dynamic fatigue loadings along the entire blade length. Once fiberglass starts to peel off from the metal base, blade integrity will further degrade and a catastrophic failure ensues because the dynamic loads are distributed over an increasingly smaller loading area. Early detection of bonding separation by reliable, sensitive and cost effective monitoring is required.

To improve wind turbine reliability and reduce overall life-cycle cost, this project focuses on developing a method for monitoring of wind turbine blades. By combining key enabling technologies, we extend the existing state-of-the-art to detect separation of fiberglass blade body from its support base at an early stage, thus help avert catastrophic failures.

Transportation of Turbine Blade on the Road

6. **Proposed Solution:** It is proposed to develop a real-time monitoring system that employs embedded strain gauges and accelerators in the vicinity of the critical fiberglass/metal base joint. Strain gauge readings reflect heightened local stress levels as the load transfer zone diminishes when fiberglass becomes increasingly separated from metal base. At the same time, vibration signature patterns also undergo detectable changes. Concurrent detection of the abnormal conditions by both devices is uniquely indicative of a loss in blade integrity. Upon reaching or exceeding a threshold level, alarm will be initiated to alert turbine operation control to take corrective action.

The following major tasks will be proposed to achieve the project objectives:

- In order to achieve fast, reliable, in field, non-destructive inspection of the blade joint, it is proposed to employ the vibration spectrum analysis. During blade transportation, if damages happen in the blade joint, such as cracks or joint weakening, it will introduce flexibility into

the blade joint, and this will alter its dynamic signatures in vibration, including dynamic stiffness, natural frequency and damping ratio. When a crack exists in the joint, it opens and closes during vibration. This introduces a changing boundary nonlinear factor into the structure, and its vibration can be distinguished from damage-free vibration even under simple impulse excitation.

- After the blades are installed onto the hub, the vibration sensor and force sensor (strain gauge) can be selectively retained in the blade joint for monitoring its long-term performance. Three versions of joints can be applied in this application, including with only force sensor, only vibration sensor and with both.

- 7. Project Deliverables:** The technical advance demonstrated in this project will be a novel method for monitoring blade joint integrity. The deliverable of the project will be a prototype blade monitoring system, validated through laboratory tests and in field tests at a partner site.
- 8. Anticipated Benefits:** If successful, this project will permit wind turbine blade manufacturers and wind turbine installation and maintenance firms to more thoroughly inspect turbine blades at manufacture and during and after installation, reducing blade scrap and eliminating costly blade replacement.
- 9. Potential Collaborating Companies:** AAAMBO Energy LLC

Project Idea #17

1. **Project Title:** Advanced Processing of Composites for Windmill Blade Manufacturing
2. **Date:** March 24, 2010
3. **Submitted by:** AvPro, 2795 Broce Drive, Norman, OK 73072
POC: Thomas Rose, trose@avproinc.com, (405) 360-4848
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** A common misconception is that the best place to go for expertise on wind blade production is to the manufacturer of these parts. This greatly limits the potential for innovation. Whether the composites are used in communication satellites or truck bodies, they share a common feature that a liquid resin is infused around fibers and converted to a solid. A second common feature is that processing methods are basically the same as those used 50 years ago. This is significant, because the options for advanced processing using computers and associated advances in resin chemistry and rheology are excluded. Thus the full range of opportunities for pilot plants and scale up to volume production cannot be effectively examined by only exploring the options currently available.
6. **Proposed Solution:** The goal of this project is to demonstrate the use of recently developed and patented pending methods of using measured cure state at the shop floor level to manage the cure process. By taking direct control of the properties critical to performance, many opportunities to reduce cost while maintaining quality are enabled. Achieving this goal will require close collaboration among companies proficient in processing science for composites (AvPro), control theory and implementation (Rockwell Automation) and material state measurement (Alpha Technologies). End use (i.e., fabricators of the composite structures) will also be tagged but in the early stages will not be the technology drivers. The goal is to innovate without legacy constraints and offer the new technology as a solution.
7. **Project Deliverables:** The technology advance will be management of viscoelastic (material state) throughout the production cycle rather assumed state based on process. While there have been many multi-million dollar studies, academic reports and research projects on this subject demonstrating the perceived potential of this approach; the application to manufacturing has been minimal.

The specific and measurable deliverable from the project (in addition to various reports) will be a working prototype installed at a fabricators site. AvPro and other key participants have significant market penetration in their areas of expertise and plan to provide commercial products for implementing the technology in the Wind Blade industry.
8. **Anticipated Benefits:** The anticipated impact upon manufacturing costs and processes will be immediate and fundamental. Current practice focuses on optimizing heat transfer in response to material supplier defined temperature cycle specifications. The benefit of this approach is to place the fabricator in control of assessing and managing the material properties by manipulating the temperature (and vacuum or pressure cycle if needed) in response to the known state of the material.

The technology transfer to and from other industries is fundamental to the proposed effort. A common condition in wind blade shops as well as aerospace and elsewhere, is the reliance on materials experts to bring tribal knowledge to the material selection and processing. While these “experts” will still be required to understand the software and application, they will be relieved of the task of communicating this knowledge of materials through “one-size-fits-all” temperature cure cycles.

The benefit to the U.S. manufacturing base is greatly increasing the value added for an hour of labor. The U.S. remains highly vulnerable to job loss where a high percentage production cost is labor. “Smart controls” reduce labor content for cure but more significantly enables more complex and highly integrated parts to be fabricated with higher value added per hour of labor resulting in fewer cure steps and less total labor.

- 9. Potential Collaborating Companies:** The customers of the core participants currently processing composites in aerospace and commercial applications. These companies include current and potential fabricators of windmill blades. The selection of collaborators for actual wind blade production will be based on their response to the proposed technology. Since the technologies and systems to implement this project are well formulated, and all tools required to demonstrate the technology reside with the key participants, presentation to fabricators can begin immediately after a project agreement is set in place.

Project Idea #18

1. **Project Title:** Advanced Control for Use in Processing of Composites for Windmill Blades
2. **Date:** March 24, 2010
3. **Submitted by:** Rockwell Automation, Inc.;
POC: Dan Carnahan and Fred Discenzo
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** A common misconception is that the best place to go for expertise on wind blade production is the manufacturer of the parts. This greatly limits the potential for process innovation and optimization. Whether the composite end product is used in communication satellites or truck bodies, they share a common feature; a liquid resin is infused around fibers and converted to a solid. A second common feature is that processing methods are basically the same as those used 50 years ago. Current manufacturer composite production methodologies use dated processing techniques and technologies, such as time/temperature profile and PID control. Updating processing methodologies is significant, because the options for advanced processing using computers and associated advances in resin chemistry and rheology are excluded in current methodologies; the full range of options based on production volume potential is not effectively examined exploring all options currently available.
6. **Proposed Solution:** The goal of this project is to demonstrate the use of advanced control capabilities using embedded intelligent agents to enhance process controls at the primary control processing level. By collaborating with domain experts in the composite material and processing field, improved control strategies using intelligent agents can be placed within the process controller at low levels to make decisions that emulate an expert in the field. Achieving this goal will require close collaboration among companies proficient in processing science for composites (AvPro), control theory and implementation (Rockwell Automation) and material state measurement (Alpha Technologies). End use (i.e., fabricators of composite structures) will also be tagged, but in the early stages will not be the technology drivers. The goal is to innovate without legacy constraints and offer the new technology processing platform capabilities based on control of material properties using material state measurement. As the systems progress to the shop, additional agents are anticipated which incorporate application specific knowledge.
7. **Project Deliverables:** The technology advance will be the demonstration of control-based agents (Rockwell Automation) at the equipment at the primary controller level. These agents will be designed to interact and learn from the higher level software (AvPro) designed to interact effectively with the domain experts and specific shop environments.

The specific and measurable deliverable from the project (in addition to various reports) will be a working prototype installed at a fabricators site. Rockwell Automation has significant market penetration in primary controls (PLC) and factory automation software. By collaborating with experts in composite material processing and material test instrumentation, commercial products will be developed for implementing this emerging technology in the Wind Blade industry.

- 8. Anticipated Benefits:** The anticipated impact upon manufacturing costs and processes will be to raise the robustness and facilitate the application of knowledge based manufacturing. A critical element for the acceptance of new technology is removing risk from implementation. By interfacing the domain expert with a robust agent, many equipment failure modes can be anticipated and avoided while also facilitating complex control actions.

The technology transfer to and from other industries is fundamental to the proposed effort. A common condition in wind blade shops as well as aerospace and elsewhere, is the reliance on materials experts to bring tribal knowledge to the material selection and processing. While the expert will remain, he will be protected from the error conditions the agent can anticipate without the need to learn fallback procedures, PID loops, and ladder logic or other control specific tasks.

The benefit to the U.S. manufacturing base is greatly increasing the value added for an hour of labor by enabling a greater use of intelligent control. The U.S. remains highly vulnerable to job loss where a high percentage production cost is labor. "Smart controls" reduce labor content for cure but more significantly enables more complex and highly integrated parts to be fabricated with higher value added per hour of labor through fewer cures and less labor.

- 9. Potential Collaborating Companies:** The customers of the core participants currently processing composites in aerospace and commercial applications. These companies include current and potential fabricators of windmill blades. The selection of collaborators for actual wind blade production will be based on their response to the proposed technology. Since the technologies and systems to implement this project are well formulated, and all tools required to demonstrate the technology reside with the key participants, presentation to fabricators can begin immediately after a project agreement is set in place.

Project Idea #19

1. **Project Title:** Next Generation Wind Blade Materials and Manufacturing Technologies
2. **Date:** March 30, 2010
3. **Submitted by:** The University of Maine, 5793 AEWC Building, Orono, ME 04469;
POC: Jacques Nader, jacques.nader@umit.maine.edu, (207) 581-2128
4. **Approximate Start Date and Duration:** September 2010 for 12 months
5. **Statement of Problem:** Currently, the overwhelming majority of composite wind blades are manufactured using thermoset matrices. Current manufacturing methods for thermosetting composite blades are time consuming, labor intensive and commonly result in quality issue. For instance, a cycle time for manufacturing a thermosetting part can be in the order of hours compared to 5-8 minutes for its thermoplastic counterpart. The fiber layup time, the infusion time, the need to avoid excessive exotherm, yet thoroughly crosslink the matrices in these massive, thick-walled molded parts are some of the many conditions that limit how fast blades can be produced using thermosets.
6. **Proposed Solution:** To address these issues, we propose an R&D strategy with the following objectives: (1) Utilize advanced thermoplastic technologies to improve durability/fatigue properties, speed up production, and create recyclable blades; (2) Use automated manufacturing techniques focused around fiber/tape-placement technology to reduce labor, speed up production, and improve quality; (3) Introduce advanced fiber technologies, (4) Accelerate the blade modeling/design/testing cycle by conducting these activities under one roof at UMaine's expanded wind energy testing lab. This research will leverage the *\$17.5M expansion of UMaine's composites Center which will provide the ability to both manufacture and test a full-scale, 55 meter composite wind blades.*
7. **Project Deliverables:** At the end of the project we will develop a new technology for using thermoplastic composites in the manufacturing of wind turbine blades. Specific and measurable deliverables:
 - Characterize and evaluate properties of advanced thermoplastic composites for wind blade applications.
 - Identify manufacturing and processing methods that maximize properties and minimize cycle time.
 - Manufacture one thermoplastic wind blade prototype using selected materials and process.
8. **Anticipated Benefits:**
 - Reduction in blade manufacturing costs by 30%.
 - Improvement in blade durability/lifecycle by a factor of 2.
 - Reduction in blade repair and maintenance costs by a factor of 2.
 - Ability to fully recycle the blades at the end of their life.

IP developed jointly under this program will be owned jointly by all parties. Once the R&D is completed, we will have a proven substitute to existing wind blade materials and manufacturing techniques. Test data and automated equipment will be used to redesign and build any manufacturer's blade. We will then approach different blade manufacturers and work with them on redesigning their blades. The application of the developed material and process can be expanded to include defense, automotive and marine applications.

Currently, the overwhelming majority of composite wind blades are manufactured in Europe, Asia and South America. However, the increasing demand for wind blades offers an opportunity for manufactures in the U.S. to compete in this market. At the 2008 Washington International Renewable Energy Conference (WIREC) Dr. Dan Arvizu – Director of the Department of Energy's National Renewable Energy Lab – estimated that U.S. composite wind blade manufacturers will be able to compete if they can increase productivity by 30%. Further, advances in the resin and manufacturing technology are needed to push the useable life of wind blades to beyond 20 years.

9. Potential Collaborating Companies:

Polystrand, advanced thermoplastic composite tapes

PPG Industries, advanced fiber technologies

UMaine, composite materials design, FEA, material characterization, prototype manufacturing, and full-scale blade testing

Project Idea #20

1. **Project Title:** Automated Process for Application and Curing of a New Safe 100% VOC Free Coating System
2. **Date:** March 30, 2010
3. **Submitted by:** Vulcan Catalytic Systems, 300 Highpoint Avenue, Portsmouth, RI 02871; POC: Michael Chapman, mchapman@vulcan-mdf.com; (401) 683-2071
4. **Approximate Start Date and Duration:** April 2010 to December 2011
5. **Statement of Problem:** The wind energy is a new fast growing segment with focus on up scaling power generation. In the manufacturing of wind turbine blades the current manufacturing procedures consist of: 1) manufacturing of the blade, 2) coating of the blade after removal from the mold with a solvent borne or water borne liquid coating. Main problems: overall production time for multi-coat epoxy primers and fillers polyurethane coatings and associated VOC emissions with exposure to workers and the environment. This counts for all current processes to protect the blade from erosion, and the environment (UV, dust, rain, ice). Due to the size most ventilation systems or suction cabinets are impractical or impossible to use. The solution is with 100% VOC free powder coatings which would solve in one step both VOC and environment issues and due to their excellent technical properties of overall toughness and long-term weather resistance. Due to the size of the composite substrate (mold and blade) and the temperature sensitive nature of the composite materials, there exists no installation to apply, melt and cure powder coatings. Vulcan is developing systems to apply and cure the powder externally as a direct replacement for the liquid coatings, as well as apply and cure the powder coating as an in-mold coating. Vulcan has aligned the cooperation of material suppliers and partners to develop a solution.

The main issue to be addressed is the development of a substrate preparation method and a method to apply, melt and cure a powder coating to a heat sensitive substrate (the interior of the mold or on the exterior of the molded blade), enabling the benefits of zero VOC emissions and allow for immediate handling after curing of the coated object (i.e., no need for long drying times for the liquid applications). The process will be (semi-) automated to improve quality and to save production time.

6. **Proposed Solution:** In order to use the benefits of powder coatings, a process should be devised to apply and cure these powder coatings in molds used to construct the turbine blades. The composite materials used to construct the molds cannot handle as high a temperature as metal molds. To solve this issue the two main points to address are:
 - Developing a curing technology that does not involve heating up an entire mold to cure the powder coating for the in-mold application, or in the case of post finishing with powder, develop a heating system that cures the powder without elevating the entire blade to the cure temperature.
 - Developing a powder coating systems that is able to cure at temperatures suitable for composites (110°C). For this purpose a collaboration with DSM has been established.

- Prepare a (semi-) automated setup to improve overall quality and to save molding time and post finishing time.

7. Project Deliverables: The technological advances demonstrated during the project will be the manufacturing of small wind turbine blade structures as a proof of principle that powder coatings can successfully be applied as an in-mold application as well as a post finishing application.

Besides reporting the following deliverables will be targeted:

- Identification of the main process parameters and tolerances. Temperature tolerances for large-scale thermo hardened composites (mold and blade). Lab-scale tolerances will be available before the project starts. Production process tolerances. The window of operation for time, temperature, heater distance, heater angle.
- Prototype of a carriage style gas catalytic infra-red (IR) unit suitable for heating the surface of composite molds and sample blade composite parts for demonstrating cured powder coating as a post finish application.
- Prototypes (a small sample unit in Europe at DSM for the powder development and a larger unit at Vulcan Catalytic Systems in the U.S. for molded samples to be fabricated) of a composite mold and a movable IR unit as mentioned in the previous point. As the wind turbine blades are large structures and change form over the full length of the blade, a movable oven construction is needed with closed loop temperature control. This will require electronic PLC controls, catalytic IR heaters supported on a gantry and a total integrated system for accurate temperature/dwell times to cure the powder.
- Small powder coated wind turbine blade like structures will be produced for simulated environmental and physical testing to prove the effectiveness of the powder coating for blade production.

8. Anticipated Benefits: Wind energy is growing fast at between 15-25% annually. In 2008 approx 20,000 turbines were installed. Production output is key by reducing molding time for the in-mold application and curing time/labor costs for the post application.

Large reduction of VOC and eco footprint. Powder coatings do not contain any VOC. The fact that no liquid painting step is need after the preparation of the wind turbine blades will result in a significant reduction in VOC (both environmental and labor related).

An installation as described in the objective will save time and floor space, the process will reduce labor costs by as much as 1/3 of the total labor content of a typical blade.

Powder coatings are characterized as tough coatings with a high durability, all these properties will reduce the maintenance costs and expensive field repairs.

The described technology is very relevant for wind turbine blades but can just as easy be applied to other composite structures that are produced in composite molds, probably the biggest is the automotive plastic.

U.S. accounts for 1/3 of the global wind energy. There are several large-scale wind turbine blade producers situated in the U.S.

9. Potential Collaborating Companies: As previously mentioned for the development of powder in mould coatings that can cure at sufficiently low temperatures (110°C) a collaboration is

sought with DSM situated in the Netherlands. The development of the powder coating is an important point in the success of the overall system but is not included in this grant application that fully focuses on the development of the curing technology based on gas catalytic IR curing technology.

Project Idea #21

1. **Project Title:** New Manufacturing Method to Rapidly Produce Wind Blade Spars with Increased Strength and Fatigue Performance
2. **Date:** March 26, 2010
3. **Submitted by:** Fulcrum Composites Inc., 1407 East Grove Street, Midland, MI 48640;
POC: Chris Edwards, cedwards@fulcrumcomposites.com, (989) 636-1025
4. **Approximate Start Date and Duration:** June 2010 to December 2011
5. **Statement of Problem:** First the size of the latest generation of wind turbines is outstripping the capabilities of the materials and techniques used to manufacture them. As wind turbines are made larger to improve efficiency, composites with improved mechanical properties and long-term performance are required to avoid premature field failures. Secondly, as wind turbines are produced in ever greater numbers, faster more consistent manufacturing techniques are required.

Current manufacturing techniques (e.g., resin infusion) are highly labor intensive and difficult to automate. This makes high speed manufacture problematic, but the degree of human involvement also contributes to lower performance due to reduced consistency. In particular the central spar members are prone to fatigue as a result of minor flaws in fiber alignment, packing density and “ply drops.” These flaws result in stress concentrations which are typically the initiation points for fatigue failure. Elimination of these flaws will allow a significant reduction in the degree of over-design required. This has multiple benefits, including reducing the total amount of material required which in turn reduces weight and material cost.
6. **Proposed Solution:** The work proposed will demonstrate the feasibility of a novel composite and manufacturing method which combines higher strength, improved fatigue resistance and the possibility to significantly increase manufacturing throughput.

It is proposed to manufacture wind blade spars in an automated process in which multiple small cross section, ultra high-strength pultruded profiles are placed within a mold and subsequently infused with a bonding resin. The use of pre-manufactured pultrusions eliminates the current fiber misalignment and packing density issues. Further these pultrusions have significantly higher strength than the current vacuum infused systems (160-220,000 psi verses 60-120,000 for current materials).

The small cross section pultruded profiles can be produced at very high speeds, directly onto large spools. Multiple spools are unwound to pack the spar mold, followed by conventional infusion to bond the profiles together. The automation of unwinding and placing the profiles, while still challenging is simpler and can be considerably faster than automated placement of dry glass mats.
7. **Project Deliverables:**
 - Material property characterization

- The production of the pultruded profiles with the stated properties has already been demonstrated at speeds up to 300’/minute. Initial small scale samples bonding multiple profiles have already been produced and have shown improved short term properties.
- The project will demonstrate the feasibility of the above manufacturing approach. A test program will systematically evaluate the variables of pultrusion size, shape, packing density, bonding adhesive etc. to optimize mechanical properties, in particular long-term tensile and compressive fatigue performance. These results will be compared against the NREL/MSU national database for wind blade composite materials.
- Large-scale prototype spars will be produced in a prototype mold for full evaluation by wind blade manufacturers.
- An automated machine for the deposition of the pultruded profiles and scale up of the process will be designed.

Predicted Properties of Proposed Composite vs. Existing

- Characterization of long-term material properties needed for design of wind blade spars.
- Production of large-scale prototype spars.
- Design of an automated profile laying machine.

8. Anticipated Benefits: Based on initial property calculations it is anticipated that the weight of a wind blade spar can be reduced by approximately 30% and the cost by approximately 20% while maintaining existing performance.

It is anticipated that the cycle time to manufacture the spar can be reduced by 50%.

The high speed pultrusion technology will be transferred from the pultrusion industry.

High speed production of large spars with superior properties has potential application in marine and infrastructure applications.

It is anticipated that the technology will be licensed to new or existing wind blade manufacturers enabling them to produce spars in house using pultruded profiles supplied by Fulcrum Composites. The proposed new composite will enable larger, more efficient wind blades to be produced, aiding the safe rapid expansion of one of the most cost effective forms of alternative energy.

9. Potential Collaborating Companies:

Innovative Composites Automation
Saginaw Valley State University
Michigan Molecular Institute
Gougeon Brothers Inc.

Project Idea #22

1. **Project Title:** Low Density Composites for Wind Blade Manufacture
2. **Date:** March 26, 2010
3. **Submitted by:** Fulcrum Composites Inc., 1407 East Grove Street, Midland, MI 48640;
POC: Chris Edwards, cedwards@fulcrumcomposites.com, (989) 636-1025
4. **Approximate Start Date and Duration:** June 2010 to December 2011
5. **Statement of Problem:** The size of the latest generation of wind turbines is outstripping the capabilities of the materials and techniques used to manufacture them. As wind turbines are made larger to improve efficiency, the weight of the blades and the gravity induced bending moment as they rotate result in extremely high stresses. Any means to reduce blade weight, especially in the outer portions of a blade offers considerable benefit in reducing material usage, reducing stresses, enhancing blade life and resulting savings in the rest of the drive train. The DOE Wind Manufacturing Workshop and the AWEA Research and Development Committee cite *"Improving quality with increasing blade lengths, design complexity, and use of lighter-weight advanced materials"* as one of the key challenges in trying to achieve 20% wind energy in the U.S. by 2030. Carbon fiber is increasingly used as a means to reduce weight due to its lower density and higher properties in spite of its significantly higher cost but is still limited. Ultra high molecular weight polyethylene fibers (e.g., Dyneema, Spectra) offer even higher property to weight ratios but have not been successfully used in composite manufacture because polyethylene has extremely low surface energy making it impossible for the matrix resin to bond to the fiber. Existing treatment techniques such as flame and corona treatment do not work with these fibers as they either destroy the fibers (flame treatment) or only partially modify the surface due to line of sight effects.
6. **Proposed Solution:** A process developed by Beholztech Inc. allows for chemical treatment of the fibers using a liquid technique. Two streams of chemicals impinge on the surface to be treated. Their reaction releases chlorine and simultaneously binds the chlorine to the plastic surface. The process has been demonstrated to raise the surface energy of olefins sufficiently to create an excellent bond for painting and adhesives. It is proposed to utilize this process on olefin fibers to raise the surface energy sufficiently to allow a resin matrix to bond thus making it feasible to use olefin fibers in conventional composite manufacturing techniques such as resin infusion. Unlike other treatment processes for olefins which are somewhat transient with time, the proposed technique permanently increases the surface energy.
7. **Project Deliverables:** The project will develop and demonstrate the viability of producing composites utilizing olefin fibers as reinforcement. The lower density of the olefin fibers combined with their high properties will result in a final composite with significantly higher specific properties as shown in the table below:

	Fiber Density	Composite Density	Tensile Strength	Modulus	Specific Strength	Specific Modulus
E Glass	2.6	1.92	1750	38	911	19.8
Carbon	1.4	1.35	1000	114	740	84
Olefin	0.9	1.05	1750	59	1666	56

Specific and measurable deliverables will be:

- Demonstration of the ability to permanently surface treat olefin fibers.
- Manufacture and full property characterization of the resulting olefin fiber composites.
- Development of process for large-scale treatment of olefin fiber tows and cloth for use in composites manufacturing.

- 8. Anticipated Benefits:** Ability to produce composites with acceptable properties and lower density will allow the manufacture of wind blades with significantly lower total weight. This will reduce the amount of material required in the root of the blade and reduce overall manufacturing costs and increase blade performance and fatigue life.

Multiple other industries and applications would benefit from high performance composites with lower density than existing materials. These include: boatbuilding, ballistic protection, sports equipment and infrastructure. In all cases weight reduction would bring significant performance improvement. An additional benefit of the olefin fiber composite is enhanced chemical resistance for applications where the poor chemical resistance of glass to alkalis limits the use of composites in aggressive chemical environments.

The proposed new composite will enable larger, more efficient wind blades to be produced, aiding the safe rapid expansion of one of the most cost effective forms of alternative energy.

9. Potential Collaborating Companies:

Beholtztech Inc.
Saginaw Valley State University
Michigan Molecular Institute
Gougeon Brothers Inc.

Project Idea #23

1. **Project Title:** Advanced Manufacturing Processes and Logistics Improvements in the Manufacture and Remediation of Wind Turbine Blades
2. **Date:** March 30, 2010
3. **Submitted by:** Manufacturing Resources Inc. (MRI), 103 Willowbrook Drive, Auburn, NY 13021; POC: Jeffrey A.Calkins, jcalkins@mri5.com, (440) 537-0311
4. **Approximate Start Date and Duration:** July 2010 to May 2011
5. **Statement of Problem:** Demand for Higher Throughput, Reduced Cycle Time, and Lower Blade Manufacturing Cost – The wind turbine blade manufacturing industry faces the dual challenges of a rapid and significant increase in production demand combined with a trend towards larger blade sizes. The worldwide demand for wind turbine blades is expected to increase threefold from 2010 to 2016. The highest volume growth will occur in the large turbine (>2.6MW) size range requiring blades in the 50-meter and greater size range. Driving the throughput time and cost reductions necessary to meet demand will require breakthrough improvements in traditional blade manufacturing methods.

Transportation Cost and Logistics Challenges – There are significant costs and logistical challenges involved with the transport of wind turbine blades from the manufacturing sites to wind farms, and from wind farms to manufacturing/remediation sites for repair during their lifecycle. As blades become larger, transport costs increase significantly and logistics issues abound. There is a major opportunity to significantly reduce lifecycle cost by “bringing the factory to the farm.”
6. **Proposed Solution:** Reduce Blade Development Time and Improve Throughput and Reduce Manufacturing Cost by Employing Available Design and Manufacturing Technologies – In recent years, new technologies have been developed that enable the use of CAD data to seamlessly drive advanced manufacturing processes such as ply-cutting, laser-guided manual or robotic layup, and blade profiling. Many of these new technologies have been applied extensively in the aerospace and marine industries, and are equally applicable to the manufacture of wind turbine blades. As both production volume requirements and the size and complexity of blades increase, employing these new technologies on a wide scale is critically important to the U.S. wind turbine industry.

Reduce Transportation Logistics Costs by Employing “Mobile Factories” for Blade Manufacture and Remediation – With the recent development and large-scale production of large, rapidly-deployable soft-walled shelter systems, currently primarily for military use, it is now technically and economically feasible to implement a “mobile factory” concept that will enable turbine blade manufacturing and remediation to occur at or near wind farms, and/or near the ports of embarkation for blades used on offshore turbines.
7. **Project Deliverables:**
 - Advanced Manufacturing Technology Investigation and Demonstration

- Demonstrate the use of a CAD-linked software tool to develop ply-cutting programs, and laser projections for both layup and blade profiling, in the manufacture of wind turbine blades. The demonstration will be performed using a wind turbine blade section or other suitable artifact, employing software and equipment furnished by the project participants.
- Investigate and report the leading-edge manufacturing technologies being employed or developed by blade manufacturers, worldwide, and recommend those technologies that appear most promising to benefit U.S. blade manufacturers.
- Mobile Factory Concept Plan and Cost Projection
 - A written report will detail the layout plan and overall estimated cost to create a rapidly-deployable “mobile factory” suitably equipped for the manufacture and remediation of wind turbine blades, onsite at wind turbine farms (and/or near the port of shipment, for blades used in offshore units).
- Cost/Benefit Analysis and Report
 - A written report will provide the projected costs and benefits to the wind turbine industry, resulting from the use of advanced technologies and rapidly-deployable mobile factories.

8. Anticipated Benefits:

- A targeted 50% reduction in the manufacturing engineering effort and calendar time required to produce the first article of a specific model wind turbine blade.
- A targeted 30% reduction in the direct labor and cycle time required to produce and profile or remediate a wind turbine blade.
- Quality cost avoidance through direct electronic transfer of design data to critical manufacturing processes.
- Elimination of transportation costs for new and remediated wind turbine blades, through the use of “mobile factories.”
- Improved competitiveness for U.S. wind turbine blade manufacturers.

9. Potential Collaborating Companies:

GFM
Knight & Carver Wind Group
TPI
Vistagy
TECO-Westinghouse
GE Energy
DHS Systems LLC

Project Idea #24

1. **Project Title:** On-the-Fly Consolidation and Cure in Thermoset Tape Laying Process
2. **Date:** March 30, 2010
3. **Submitted by:** Center for Composite Materials, University of Delaware, Composites Manufacturing Science Lab, 2 South Academy Street Delaware Av., Newark, DE 19716; POC: Dirk Heider, heider@udel.edu, and Shridhar Yarlagadda, yarlagad@udel.edu, (302) 831-8898
4. **Approximate Start Date and Duration:** July 2010 for 24 months
5. **Statement of Problem:** This project will develop an automated thermoset prepreg placement system with integrated heating to enable on-the-fly placement, consolidation and curing of large-scale composite components. The system will rely on sequential heating and cure of the substrate while placing each additional layer of the incoming tape which effectively anneals and consolidates the tape interface properties.

Current tape placement machines tack the prepreg material onto the mold and substrate surface while applying a minimum amount of heat. After final placement of the material, the complete mold structure is bagged and placed in an oven or autoclave to cure. The additional bagging of the mold is labor intensive, with costs increasing exponentially with part size and in case of the autoclave curing step requires large capital investment and operating expense. Together, both steps significantly increase overall cycle time and reduce mold usage. The proposed process would eliminate these additional processing steps as the prepreg is consolidated during layup while relying on existing commercially available equipment for thermoset tape laying. The adaptation of this approach requires an updated head design and improved understanding of the curing and consolidation process leading to significant improved properties, cycle time and costs.

6. **Proposed Solution:** In order to enable in-situ consolidation and cure of thermoset composites during tape placement, both material and process conditions have to be optimized for the specific process. The thermoset resin system has to have short gel and cure time to allow short heating zones and fast lay-down rates. Ideally, the first placement will provide sufficient tack of the incoming tape to the substrate and heating/pressure from subsequent layer placements will increase consolidation and cure levels. The cure profile of the resin needs to be tailored to accommodate this methodology, so that sufficient strength/stiffness build-up occurs to retain consolidation during this process. This will ensure better compaction than the standard vacuum process and accordingly better fiber content and low void fractions.

The heating/pressure system on the tape placement head must be designed to provide the necessary capability to heat/consolidate more than just the incoming layer. Ideally, a heating method that provides penetration depth is preferred, which will enable curing and consolidation of underneath layers during the process. Pressure application will require conformable rollers to accommodate curved surfaces. Variables including levels of pressure, length and width of heating zones, number of heating and pressure zones, etc. will need to be optimized.

This project will investigate the material and process requirements for this particular tape laying process. It will leverage existing modeling tools developed at UD-CCM over the last decade to better understand the compaction and heating conditions necessary to accomplish the required cure and void content profile. Previously developed models for heating and consolidation of thermoplastic tape placement will be combined with thermoset cure kinetics, to enable complete model-based process optimization. We have demonstrated this previously successfully for thermoplastic tape placement.

All facilities necessary for this effort are also available at UD-CCM or our industrial partners, including an ABB 6400 six-axis robot system, several heat sources (hot-gas, IR, near-IR, induction) and a multi-stage experimental laminator that allows us to perform model experiments with tape placement process parameters on flat laminates.. The system has the necessary drive system for velocity control, heating stages, consolidation rollers and cooling stages. Appropriate thermoset prepreg systems will be selected by evaluating cure-kinetics and the experimental laminator will be used to validate the modeling approach and demonstrate that our proposed methodology for in-situ consolidation and cure of thermosets is viable.

7. Project Deliverables:

- Define material and process requirements for on-the-fly cure and consolidation processing.
- Develop a modeling framework to predict material state (cure, consolidation) as a function of material and process parameters.
- Experimentally validate approach.

8. Anticipated Benefits:

- Improved material quality – improved overall mechanical properties of the composites as high local pressures will result in increased fiber volume content and reduced void content.
- Reduced cycle time – allows simultaneous placement and cure of the prepreg and can potentially avoid post-cure of the component.
- Reduced cost – lower capital investment as curing oven or autoclave are not required; reduced fabrication time allows better mold utilization.

9. Potential Collaborating Companies: Three industrial partners have been contacted. Kubota, a small business in Delaware, has developed a new near-IR heating source which will be evaluated for bulk heating allowing increased lay-down rates. Ingersoll Machine Tools Inc. is one of the premier tape laying equipment manufacturer and will be consulted on scale-up issues for their current tape laying head design. Gamesa US has a collaborative agreement with the University of Delaware and will consult on potential implementation issues in a real wind blade manufacturing environment.

The proposed development will provide an efficient and repeatable manufacturing approach to automate the wind blade fabrication in the U.S. and abroad. U.S. manufacturers need to reduce touch labor and improve cycle time to stay competitive against low-cost importers. U.S. equipment manufacturer will be able to sell the system not only in the U.S. but worldwide.

Project Idea #25

1. **Project Title:** Methods to Improve the Manufacturing Quality of Wind Turbine Blades
2. **Date:** March 29, 2010
3. **Submitted by:** Triton Systems, Inc., 200 Turnpike Road, Chelmsford, MA 01824;
POC: Tom McDonald, tmcdonald@tritonsystems.com, (978) 479-8461
4. **Approximate Start Date and Duration:** July 2010 for 12 months
5. **Statement of Problem:** As the scale, production demand and service lives of wind turbines increase, ever larger numbers of composite blade structures need to be inspected and assessed, often redundantly and with different inspection instruments and devices for different types of defects in the same area of the structure. The increased time commitment to accurately perform such inspections will be prohibitively costly if not automated. Undetected defects can lead to catastrophic failures, resulting in downtime for the turbine, costly repairs and the potential for human casualties and property damage from liberated parts. As the power industry increasingly relies on wind, it will not accept the liability and service interruptions of such failures. For the wind power industry to even approach the level of reliability achieved by commercial aviation or gas turbine power generation industries, it will require significant automation and high throughput inspection methods to provide high confidence in the detection of the most common production defects: fiber wrinkles, fiber waviness and resin disbond or void conditions.

For composite structures, the relationship between a defect and its effect on component life is less obvious than for metals. “Defect vs. component life” is not as well understood, or as linear, as for metal structures. The need is therefore for more detailed defect characterization, preferably in three dimensions. To ensure that these inspection operations do not increase the amount of time (and cost) allocated for non-destructive inspection (NDI) of new parts, it must be performed accurately, rapidly and automatically with a delivery platform that can be adapted to different sized components, scanning requirements and NDI equipment. It is also desirable to accurately document the location of any defects and digitally map them on a surface model of the blade component. This could be used to track the history of certain types of defects over time for each blade and to even compare the history of the entire product line relative to certain locations and types of defects. Fiber waviness in composites is a major problem when dealing with radical transitions of composite laminates from thick to thin sections, such as encountered in most wind turbine blade spars and spar caps. The OEM/Design Authority needs to specify the maximum allowable deviation from the designed direction. An appropriate fiber waviness NDI technique should measure the fiber orientation in a given plane and, if it is beyond the allowable deviation, take other measurements (e.g., volume of the wavy or wrinkled area). In addition, fiber wrinkles do not necessarily grow over time. An appropriate fiber waviness modeling and analysis technique is needed. This involves non-destructive evaluation (NDE), which can characterize a specific defect in terms of its effect on the local geometry. Most of the critical material properties for carbon-fiber reinforced polymer (CFRP), such as void volume fraction (porosity) and fiber volume fraction (FVF), are currently measured indirectly using ultrasonic parameters related to bulk properties. These provide through-thickness averaged values of the measured ultrasonic parameter in the inspected region. With waviness, however, the issue is that, in a very specific area, the ability of the structure to handle certain loads is severely compromised. Direct

measurements of material properties would be of more use to structural designers and process-control managers, especially if they could be mapped as a function of 3D location. This would also allow future structural designers to vary the acceptance criteria on these parameters depending on the predicted stress at each location, resulting ultimately in lighter, less conservative structures.

6. Proposed Solution: TSI proposes to develop and demonstrate a non-destructive composite inspection method to rapidly identify, characterize and disposition:

- The location of in- and out-of-plane fiber waviness across a swath of composite structure (e.g., a blade root or spar).
- The location and severity of voids, delaminations and disbonds along the entire surface of spar cap-to-skin, spar-to-skin, and/or skin-to-skin bond lines.

The proposed solution initially incorporates single-element focused-probe and/or phased array ultrasonic (UT) inspection to provide full waveform capture of inhomogeneous, anisotropic, multi-layered composite materials. The proof-of-concept demonstration would also incorporate thermography to detect voids, delaminations and disbonds at the near-surface bond line between skin and spar-cap. The methods would be optimized for conditions specific to the representative coupons provided by Sandia National Labs, and our partner OEMs – Knight & Carver and Clipper Windpower. For the ultrasonic inspection, the resulting data collected would be imaged as B-scans and C-scans, and subsequently presented as a 3D representation and analyzed to quantitatively assess wrinkle volume, wavelength and severity in terms of maximum ply angle. For the thermographic inspection, the images will be tagged to specific locations on the CAD model and the deviations quantified through image processing. A cost model would also be developed for the total cost to scale up to a production ready system and also to estimate the impact on total manufacturing cost for small, medium and large-scale wind turbine blades.

7. Project Deliverables:

- Automated data acquisition and analysis for defects described above in representative coupons of laminated composite structures will be demonstrated.
- A cost model will be developed for the automated data acquisition and analysis concept to measure productivity metrics.

8. Anticipated Benefits:

- Optimized NDI methods increase the probability of detection (POD) of waviness of a certain size in a given structure, regardless of depth of location.
- Post-inspection data manipulation provides full characterization of the wrinkle to enable a design engineer to assess its impact on component strength and life.
- Automation of the inspection process itself ensures higher reliability than do current handheld techniques and inspection labor for 100% inspection will be reduced by more than 50%.

- The potential to transfer this technology to other industries is very high. The military and commercial aviation industries worldwide face the same problems and need the same solution. There are no anticipated tech transfer issues from wind turbine to aviation.
- The potential benefits to U.S. manufacturing base are higher reliability composite components achieved through automated data acquisition and data analysis systems to minimize costs.

9. Potential Collaborating Companies:

Sandia National Labs
QinetiQ USA
Knight & Carver
Clipper Windpower
TPI Composites/GE Energy

Project Idea #26

1. **Project Title:** Advanced Manufacturing for Modular EHD Wind Energy Technology
2. **Date:** March 31, 2010
3. **Submitted by:** Accio Energy, 3600 Green Court, Ann Arbor, MI 48105;
POC: Dr. Dawn White, dwhite@accioenergy.com, (734) 260-3483
4. **Approximate Start Date and Duration:** June 2010 for 12 months
5. **Statement of Problem:** In turbine based wind energy technology generation capacity is tied directly to design; i.e., for each and every desired output, a specific product design for components such as blades, generator, hub, transmission, etc. is required. Part commonality between a 100kW and a 1MW wind turbine is essentially zero. As a result, to meet market needs for wind energy at varying scales, a large number of unique product designs are required. This means that it is difficult to achieve economies of scale in design, testing, and manufacturing of wind energy products. In 2008 the largest selling producer of wind turbines in the U.S. sold 2,500 units. The U.S. was about 30% of the world market, so assume total 2008 sales by this producer of 7,500 units. Two product sizes were available, so we can estimate that 4,000 units would be at the high end of product volumes with many of the over a dozen large turbine producers selling far fewer. These low volumes are characteristic of industries such as aircraft manufacturing which do not support significant manufacturing economies of scale, particularly for very large components such as those found in turbine blades, generators, gears and hubs.
6. **Proposed Solution:** The goal of this project is to demonstrate that a modular wind energy technology based on electro-kinetic (E-K) wind energy principles and employing automotive heritage manufacturing techniques and modular platform design concepts can result in significant cost reductions for wind energy systems at a range of sizes from 100kW to 2.5MW. E-K wind energy systems use wind energy to separate positively charged water droplets from their negatively charged sources, creating a high voltage direct current generator, with roughly the same water consumption as coal or natural gas plants, and only 10% that of nuclear generation. E-K wind systems can be stationary, silent and modular like solar panels as they do not rely on rotating motion like conventional electrical generation.

Like solar panels, E-K wind energy systems are composed of modular panels of fixed capacity (e.g., 5kW), which can be assembled in multiples to produce a desired system output. Thus a 50kW system would incorporate 10 5kW modules, while a 500kW system would employ 100 modules. Like solar systems, these modules would be sold to developers in any quantity required. By replacing literally dozens of complex, low volume wind system products with three or four standard modules with outputs ranging from perhaps 2.5kW to 20kW, product volumes will increase dramatically, allowing enormous economies of scale. Objectives include a prototype scale demonstration of the applicability of high volume, high precision enabling manufacturing technologies, and the development of a product platform roadmap and cost model.

7. Project Deliverables:

- Demonstration that the core technology can produce a commercially viable output.
- Demonstration that high volume, precision manufacturing technologies, such as those used in the automotive sector can be implemented for E-K wind system fabrication.
- Validated cost model showing that costs lower than conventional wind turbines can be achieved in community and offshore wind applications based on a modular E-K wind energy technology platform.

8. Anticipated Benefits: This project is specifically targeted at transferring automotive manufacturing technologies and economies of scale to wind energy implementation, by dramatically reducing the number of discrete parts in a wind energy system and employing the high volume, high precision processes used in automotive power train manufacturing. A utility scale wind turbine has roughly 8,500 components, nearly all of which are different for every turbine capacity produced. An E-K wind system in contrast will be composed primarily of highly engineered tubing which will be cut to length, and used to produce modular panels of a standard capacity, for example, 10kW, resulting in a part count reduction of 50-75%. Wind systems of arbitrary capacity will be constructed from multiple panels in the same way solar panels are combined to produce a desired output, from rooftop residential systems to MW utility scale installations.

As a result, high volume manufacturing process commonly employed in automotive manufacturing can be applied to the manufacturing the E-K modules. We anticipate that the impact will be a 50% reduction in manufacturing and product costs.

Potential benefits to the U.S. manufacturing base are considerable. This effort is aimed at re-purposing underutilized automotive manufacturing facilities and human capital, both engineering and labor, to create a new wind energy product category. The desired outcome will be increased job creation, product exports, and increased clean wind energy capacity.

9. Potential Collaborating Companies:

Ford
Altair Engineering
Brazeway
Boeing

Appendix B – Detailed Final Report for Advanced Manufacturing for Modular Electro-Kinetic (E-K) Wind Energy

1.1 Conversion Technology

Electrohydrodynamic (EHD) wind energy technology is not based on electromagnetic physics, rather the systems operate on a principle of charge separation in which the kinetic energy of the wind is used to drive positive charges, carried on ambient or supplied charge carriers, away from their negatively charged source, to harvest wind energy.

EHD wind energy is a form of non-turbine wind energy conversion which does not operate based on electromagnetic physics, but exploits E-K principles, directly converting kinetic energy to electricity. EHD systems emit small amount of water as an electrically charged mist, then use wind energy to push these charges away from their source, against the electric field that arises from the charge separation. The wind's kinetic energy is converted to high voltage direct-current energy to supply power to users. The EHD system is analogous to a wind-driven capacitor that produces a continuous usable current rather than a discharge. A load applied to the circuit harvests the usable current. An even more potent analogy may be the thunderstorm. In a thunderstorm, high speed rotational winds impose electrical charge on droplets through poorly understood tribo-charging methods. Driven by thermal gradients between the top and the bottom of the clouds (which are driven by their heights of up to 16km or so), these charges separate. Again, the mechanisms are the subject of scientific debate, although it seems to be generally agreed that it is driven by the varying rates at which water droplets and ice particles move up and down in the clouds and their varying charge to mass ratios. The tops of the clouds become highly positively charged, while the bottoms are highly negatively charged – in effect, they are large

capacitors. When the breakdown voltage of the dielectric (the moist air in the cloud) is reached, a lightning bolt results.

An EHD wind system is “an engineered thunderstorm” in the sense that we want to take that process, operate it at the “normal” wind speeds prevailing 50-300 feet above the ground, and harvest energy continuously rather than intermittently. This is accomplished by emitting a controlled spray of very small droplets with a specific positive charge to mass ratio into the wind. These droplets are pushed to ground by the wind, against the opposing system electric field which is the result of the separation of the positive charges from their negative counterparts. The origin side of the system rises to a high negative potential. When the desired system potential is reached (~150kV) a load is applied, and excess current is drained from the system, resulting in a high voltage direct-current (HVDC) generator, as shown in Figure B-1.

EHD wind energy conversion has the potential to enable major expansion in wind energy use by major utilities, wind farm developers, and industrial customers, drastically reducing greenhouse gas emissions, transmission losses, and new transmission capacity requirements. Key to this is the potential for EHD wind to be:

- As modular as solar panels, yet cost competitive with large wind and fossil fuel based generation.
- Visually inconspicuous, silent in operation, and safe for wildlife.
- Fabricated using recycled materials and manufacturing capacity well established within the United States (U.S.).

Figure B-1. EHD Wind Energy Operation

Like solar panels, E-K wind energy systems are composed of modular panels of fixed capacity (e.g., 5kW), which can be assembled in multiples to produce a desired system output. Thus a 50kW system would incorporate 10 5kW modules, while a 500kW system would employ 100 modules. Like solar systems, these modules would be sold to developers in any quantity required. By replacing literally dozens of complex, low volume wind system products with three or four standard modules with outputs ranging from perhaps 2.5kW to 20kW, product volumes will increase dramatically, allowing enormous economies of scale.

1.2 Prior Research

EHD wind energy is not a new concept. Like many other alternative energy technologies being studied today (synfuels, algal biomass, etc.) considerable research was performed on the topic in the 1960s and 1970s by DOE and DOD funded researchers. However, efficiency was low and the work was not commercialized. More recently a single study was carried out at Delft University in the Netherlands but it ended

in 2008 and to the team's knowledge no significant effort outside Accio Energy is ongoing in this field.

Figure B-2 synthesizes the prior work. Marks conducted research using high pressure sprays up to 150 psi, and Schurig also employed high pressure sprays. Neither was able to operate systems that produced more power than was used in producing and charging the droplet spray. Minardi and Lawson utilized a push type field arrangement with two charge collecting columns downwind of the emitter to set a field voltage. Under grounded conditions, using corona-charged water droplets, they collected a maximum of 340 microamps of current, which is substantial, but it was insufficient to achieve energy positive output with their arrangement. Djairam's research is extensively documented in his Ph.D. thesis, and was primarily focused on application of novel spray systems to the problem of EHD wind systems. He tested on a

Team	Year	Fluid Pressure	Droplet Diameter	Droplet Charge	System Field	Space Charge	Electric Field Mgmt
Schurig	1979						
Marks (DOE)	1980						
Minardi & Lawson (DOD/DOE)	1981						
Djairam	2008						
Accio Energy	Present						

Figure B-2. Prior Research in EHD Wind Energy

very small scale, and measured power output indirectly via system capacitance rather than a load. As a result, his conclusions on power output are of little value, since the biggest difficulties associated with EHD wind energy generation occur as the number of spray sources present increases past 5-10 sources and when the system is forced to operate under load.

A key shortcoming of previous research has been an absence of work that considered all of the complexities of EHD wind energy; it is a multi-physics problem in which dispersed phase fluid mechanics, electrostatics, and atomization science converge. Accio Energy is the first organization to have taken a full spectrum approach as discussed in the following portions of this report covering the technical development aspects of the project.

1.3 Technical Section

As discussed in the following portions of the report, and illustrated in Figure B-3 there are three core competencies associated with the development of a commercially viable EHD wind energy system:

- Electric field management
- Charge carrier engineering
- Multi-physics system modeling.

Figure B-3. EHD Core Technologies

In addition, it is critical to be able to operate safely and obtain high quality data at very high voltages. Accio Energy has made very substantial progress in each of these areas during the term of the project. In particular, improved electric field management, in concert with better high voltage design and safety procedures allowed the team to achieve operating voltages in excess of 200kV, a critical milestone for operational efficiency in EHD wind systems.

1.3.1 Technology Development Objective

The Accio/Boeing team's objective was to create a novel, efficient, cost-effective non-turbine based technology for generating power from renewable wind energy. This technology

will be embodied into Aerovoltaic™-brand wind energy generation systems that will use wind energy to separate charged water droplets from their source to create an electric current without moving parts. Planar, translucent and wind permeable panels, composed primarily of engineered tubes and configured modularly in sizes from 2kW to 20kW will supply charged water droplets into the wind to generate electricity. Power conditioning will be modular and ground-based rather than tower-based for ease of installation and maintenance. Customers will combine the modules to install grid integrated generation capacity up to and beyond 1MW.

This team is the first ever to design, test, and repeatedly demonstrate meaningful net positive energy with multiple prototypes that incorporate a patent-pending electric field management design breakthrough. Accio has developed the first ever comprehensive 3D multi-physics model of system potential; going beyond the largely analytical approaches of other researchers. The company has proved its technical concept and as part of this project showed a path to scale this highly manufacturable technology into a commercially powerful game-changer.

1.3.2 Accomplishments During Project

Accio worked with Boeing in this project to demonstrate the feasibility of developing readily manufacturable modules that win on both features and costs for onshore and offshore utility-scale installations closer to population centers. In this project the Accio/Boeing team used advanced modeling, and prototype fabrication and testing to show a clear path to achieving target power density, use of rapid prototyping and tooling to accelerate development, and low-cost manufacturing approaches in a product.

Three key accomplishments were:

- 10X total output
- Predictive model guided innovation
- Manufacturability.

1.3.3 Approximately 10X Increase in Energy Density in Prototype Performance

Over the course of this project, the output produced by operating EHD prototypes increased as shown in Figure B-4.

At the beginning of this project in December 2010, the net output of an EHD wind system was less than 0.1 W/m^2 . At the end of the performance period, the output was in excess of 5 W/m^2 .

A combination of developments led to this overall achievement.

- Achieved system operating voltages over 200kV (from <80kV). Since the power from a wind energy (or any generator) is the product of the generator current and voltage [Power = current (I) x voltage (V)] achieving a high system voltage, is particularly important in an EHD wind system in which current flow is limited by

Figure B-4. EHD Wind Energy Power Progress

charge carrier characteristics and the space charge limited flow in the system. Attaining very high voltages is a major design problem, which was addressed by a complete redesign of certain system hardware, in particularly the arrangement of load resistors and data acquisition. This resulted in the ability to work consistently at voltages of up to 220kV, and a nearly 3X increase in total power out of the system.

- Electric field considerations were a key area in which the shortcomings of prior research limited achievement in EHD wind energy generation. Accio Energy identified developments in this field as critical prior to the start of the program, but improved electric field management design during this effort to increase total system output 2X, and improve manufacturability. Prior generation field shaper designs increased jet interaction. As part of evaluating manufacturability an opportunity was identified to change the field shaper design to reduce shorting to a configuration that will enhance future manufacturing scalability.

1.3.4 Developed First 3D Multi-Physics Model of EHD Wind Energy Technology

Accio Energy started the NCMS project with rudimentary modeling capabilities; quasi-2D models of drag forces on droplets, and 2D models of the electric field environment in an EHD wind generator. Over the course of this effort, Accio developed a 3D multi-physics dispersed flow model in FluentTM of fluid droplets in an air flow, with fully coupled electrostatic effects (Figure B-5). This involved considerable customization, including the development of User Defined Functions (UDFs) to incorporate the electric field effects. This high fidelity model simulates the real world

conditions in an EHD generator, and is a powerful tool for predictive innovation. It accelerated development by allowing many new design concepts to be validated via modeling prior to the time and cost risks of major investments in test hardware. A number of important accomplishments flowed from this (Figures B-6 and B-7).

Figure B-5. EHD Multi-Generation Modeling

Figure B-6. Model Output Illustrating Electric Field Direction and Magnitude Near a Nozzle Tip

Figure B-7. Model Output Illustrating Particle Tracks of Charged Droplets Sprayed into the Wind in an EHD Generation

- Using 3D model, identified key innovations in droplet formation and charging approach required to achieve target output of $>100\text{W}/\text{m}^2$.
- Validated 3D model using current spray source technology to verify that the model results projecting commercially viable output are reliable.
- Identified important characteristics of droplet formation processes.

Very critically, this powerful model continues to provide key insights regarding the level of impact of various process parameters on total system power output, supporting ongoing innovation at Accio Energy.

1.3.5 Prototyping and System Manufacturability

Due to the novelty of the EHD wind energy technology, fabrication of test articles requires large numbers of custom fabricated components. Project participant Boeing contributed extensively to the prototyping efforts and to a focus on manufacturability at all stages of design and conceptualization.

1.3.6 Prototyping

Boeing has world-class resources in additive manufacturing/rapid prototyping which were deployed in this effort. These were used primarily in the development of new technology for droplet formation and charging. Droplet formation is an area where ability to fabricate custom spray sources rapidly and at low cost is highly value adding. Figures B-8 and B-9 are a pintle nozzle designed by the Accio team and fabricated by Boeing for testing at the Accio Energy laboratory. The complicated, fine features of this design would have been very time consuming and costly to produce using conventional methods. It was built on a stereolithography (SLA) machine at Boeing in a few days at modest cost for this effort.

In addition, the utility of incorporating airfoil shapes into the electrostatic elements of the EHD generator were investigated. Model results had indicated that the improved airflow through an EHD generator resulting from incorporating such cross sections could have performance advantages. Creating custom components with air foil cross sections is costly using conventional methods; use of selective laser sintering at Boeing allowed a variety of components to be

Figure B-8. Pintle Nozzle Design

Figure B-9. Pintle Nozzle Build via SLA

produced in modest quantities for testing at a low cost (Figure B-10).

These tests were conducted quickly and at low cost, allowing both specific designs and broader design concepts, in this case, use of large ring shaped electrostatic features, to be evaluated. The results showed that this particular design, while promising, was not scalable. Accio Energy is developing alternative prototype test hardware that is more readily manufacturable than previous generation hardware, with improved total energy output performance.

The EHD wind energy solution being developed by Accio Energy can use high volume manufacturing to change this completely, providing U.S. industry with a huge opportunity to disrupt the market, increase manufacturing leadership, and drive exports in an important technology. At a time of concern for improving national energy and economic security, the results of this project are well aligned (Figure B-11).

Hypothesis: airfoil cross section will improve EHD generator efficiency

Modeling: results show that an increased current flow may be possible

Prototypes in a ranges of sizes were produced at Boeing via Selective Laser Sintering

Initial small scale testing was conducted to test without jet interactions

Larger scale testing to validate results led to further design revisions

Figure B-10. Airfoils From Design to Prototype

Figure B-11. EHD Wind Enhances National Energy and Economic Security

Appendix C – Detailed Final Report for Hybrid Laser Arc Welding for Manufacture of Wind Towers

1.1 Statement of the Problem

In its July 2008 report, 20% Wind Energy by 2030, the Department of Energy noted that in order to achieve the goal of 20% wind energy, 79,130 land-based turbines and 17,976 offshore turbines would need to be installed between 2007 and 2030. This amounts to 239.5 GW of land-based wind capacity and 53.9 GW of shallow offshore wind capacity, for a total of 293.4 GW [1]. Practically speaking, this amounts to increasing the number of wind turbine installations from approximately 2,000 per year to nearly 7,000 between now and 2017 [2].

While this goal is feasible, the report also noted that two of the continuing barriers to greater penetration of alternative energy in the United States (U.S.) are the financial capital required to install new factories, and the technology development required to reduce the cost of manufacturing alternative energy systems themselves.

For example, the Department of Energy noted the following [3]:

“One wind blade manufacturer with significant international manufacturing experience estimates that, to make a U.S. factory competitive, the labor hours per blade would need to be reduced by a factor of 30-35%. To ensure that the bulk of these manufacturing jobs remain in the U.S., automation and productivity gains through the development of advanced manufacturing technology are needed. These gains will allow the higher U.S. wage rates to be competitive.”

The goal of this research project is to reduce the cost of alternative energy manufacturing of

wind towers and thereby to increase U.S. competitiveness globally through introduction of hybrid laser arc welding (HLAW) into the supply chain for manufacturing wind towers.

1.2 Proposed Solution

North American wind tower fabrication for GE accounts for greater than 120,000 man-hours of welding annually. One way to reduce manufacturing costs for wind towers is to utilize HLAW. HLAW has the potential to enhance productivity, while reducing energy consumption, to offset the foreign low-cost labor advantage and thereby enhance U.S. competitiveness. HLAW technology combines laser welding and arc welding to produce an energy efficient, high productivity, welding process for heavy manufacturing. This process leverages the ability of the laser to produce deep weld penetration and the ability of gas metal arc welding (GMAW) to deposit filler material, thereby producing stable, high quality welds on joints with gaps and mismatches typical of those seen in heavy manufacturing.

In 2009, GE Global Research (GEGR) installed a HLAW facility that is unique in North America. This system consists of a 20kW fiber laser, coupled with an 8-axis robotic HLAW equipment. A picture of this system is shown in Figure C-1.

With this equipment, GEGR demonstrated the feasibility of welding wind tower structural steel in thicknesses required for the 80m towers that support GE's 1.5MW wind turbine. In addition, GEGR conducted experiments to evaluate the capability of the technology to handle plate fit-up gaps typically seen in tower manufacturing.

Figure C-1. HLAW System Installed at GEGR

This systems consists of a 20kW fiber laser, a MIG power supply and wire feeding system, and a robot for motion control

1.3 Task 1 – Equipment and Safety Considerations

1.3.1 Functional System Guidelines

The welding routines used over the duration of this project are comprised of three separate welding passes. One laser hybrid welding pass is utilized and two submerged arc passes are used. The laser process is applied to penetrate the thick land section marked “L” in Figure C-2, while the submerged arc process is used to fill grooves “G1” and “G2”.

The headings that follow discuss some functional system guidelines for the hardware required to successfully weld joints with this process sequence.

Figure C-2. Representative Joint Geometry for Plates Welded

1.3.1.1 High Power Solid State Laser System

This laser could potentially be either a fiber or disk or disk style laser. In a manufacturing setting implementation of a beam switch would likely be considered to allow for resource sharing of this high capital cost asset (Table C-1).

Table C-1. Functional System Guidelines for Laser Components

Requirement	Desired Function
High power >15KW CW	Penetration capability exceeding 16mm in steel
Fiber delivered beam	Ease of use and implementation
<=200 micron fiber core	Ability to attain tight focus and high energy density
Reliable focusing head	Robustness against focal shift and thermal instability

1.3.1.2 Gas Metal Arc System (GMAW or MIG)

This GMAW equipment should be capable of pulsed operation and high duty cycle automated welding (Table C-2).

Table C-2. Functional System Guidelines for GMAW Components

Requirement	Desired Function
400+ ampere continuous rating	Ability to meet fill requirements for high gap HLAW welding
Push pull torch	Feeding precision and accuracy
Water cooled barrel	Durability at high ampere/high duty cycle
Flexible AC operation	Ability to manipulate pulse waveform to meet joining process requirements

1.3.1.3 Submerged Arc Welding System(s)

A tandem SAW system with high capacity 1000A AC/DC power supplies is recommended for filling the groove geometries utilized in this project. Lower amperage supplies or DC only machines could be utilized but this would have a negative impact on the productivity and efficiency of the capping process (Table C-3).

Table C-3. Functional System Guidelines for SAW Components

Requirement	Desired Function
AC/DC Operation	DC operation for high penetration schedules and AC operation for high deposition schedules
1000A ampere rating	Deposition and penetration
Tandem/dual head	Tandem operation for high deposition rates

1.3.1.4 Seam Tracking System

A laser seam tracking system provides accurate, high-speed automatic control of the welding head (laser/MIG) position. This improves weld quality while removing the need for an operator to monitor and/or adjust the weld head or work piece (Table C-4).

Table C-4. Functional System Guidelines for Seam Tracking Components

Requirement	Desired Function
Camera accuracy	Ability to resolve narrow & deep groove geometries used in laser joint designs
Stage & positioning accuracy (Z,Y)	Ability to plate the laser beam within 25% of the laser beam diameter
Speed capability	Ability to track joints at speeds exceeding 2m/min

1.3.1.5 Motion System

A motion system is required to carry the welding process across the seam being welded or to position the welding process above a part being moved. If sufficient precision local motion/tracking systems are implemented for components such as the laser and SAW equipment the precision of the gross motion system need not be too high (Table C-5).

Table C-5. Functional System Guidelines for the Motion System

Requirement	Desired Function
Capacity greater than 2000 lbs	Ability to carry SAW and laser welding equipment in addition to controls and operator
Speed greater than 2m/min +/-5%	The laser process sets this requirement in that stable welding parameters are found near 2m/min travel speed
Speed capability	Ability to track joints at speeds exceeding 2m/min

1.3.2 GEGR Equipment Set

At GEGR, the above functional equipment requirements were evaluated against available resources, and an equipment set was assembled for the welding of test panels in this project.

1.3.3 Introduction to Safety Considerations

There is more than one avenue of approach that will provide a safe environment for a welding demonstration and comply with local, state, and federal regulations. Safety rules and regulations are designed to standardize, codify and help manage reduction of risk to damage of humans, equipment and the environment. In some cases, the equipment can be made inherently safe, in others the equipment is inherently hazardous, but can be used safely (e.g., power saws).

In the case of a demonstration of the hybrid welder, the “pathways” or avenues of approach can be characterized by identifying one avenue as “product” oriented, whereas the other approach would be identified as a more “procedural” or administrative control methodology. The product approach necessarily contains engineering features on the product which render some level of hazard protection (laser hazard classifications). Therefore the product approach may represent greater investment in the equipment and its engineering development. Nevertheless, the product approach is probably the preferable path in the long run, for use in production by trained operators.

In fact, if total Class I product compliance is attained, it permits reduced requirements on workplace safety management pursuant to the user standards. On the other hand, for purposes of a demonstration only, there may be less investment of design time in implementing a “procedural or administrative control system”. This means more labor to plan and control, and for the establishment of official positions of safety responsibility. This path also would require construction of a barrier on all 4 sides, with interlocked entry points, constituting an LCA (Laser Control Area), intersecting the otherwise large NHZ (Nominal Hazard Zone i.e., the zone defined by the radius within which the Maximum Permissible Exposure (MPE) is exceeded). Workers who enter into the laser

area would be required to wear laser specific eyewear PPE (Personal Protective Equipment) with Optical Density (OD) adequate to provide a level of protection from this particular laser wavelength; The LCA will be restricted (by interlocks and Warning Signs) to authorized persons, only, and the safety instructions to the user about hazards and hazard avoidance will need formulation and promulgation. Further, the site would need to develop, and implement, a program for local compliance and safety management of the LCA and the surrounding work area....just for the demonstration, itself. Because the choice between paths was not immediately clear, we determined that this report will outline the choices (as well as some elements which are not optional) to begin to refine the decision on an approach to take.

1.3.4 Potential Safety Paths

Equipment: Without regard to which avenue is chosen, compliance with the U.S. Federal Laser Product Performance Standard and/or IEC/EN/CSA 60825 is imperative. Although it might be arguable whether a demonstration product is “entering commerce,” since interstate, or even international transport would be required, there is ample reason to justify that defining the performance (and filing with U.S. CDRH/FDA) is prudent, and form a baseline for safety and liability protection. The FDA/CDRH is responsible to enforce 21 CFR, including laser product compliance and certification (21 CFR 1040). The U.S. Federal Laser Product Standard is compatible with and acceptable to all North American laser regulations and compatible with the requirements of other locations around the world. Under the standards inherent to the U.S. and international regulations, any product which incorporates or is intended to incorporate a laser, or laser system, is itself a laser product. Under these regulations, there are two potential classes for the proposed demonstration equipment: a) a total enclosure, such that all hazard is contained within the protective housing, which is Class I; or b) a product with

controls and guards which enable limiting the exposure to hazard, but for which the beam

remains accessible, which is Class IV (Tables C6-C8).

Table C-6. Hierarchy of Safety Requirements

Category	FDA/CDRH	OSHA	User Location	Liability	Operation
General Statement	All Laser Products, regardless of design or hazard class, must be reported	Required for job site safety regardless of hazard class of laser User will make their own SOP for safety, eventually, but we will create <i>pro forma</i> document for this demonstration	Compliance with regional, national and provincial (State) requirements for workplace safety with lasers	Liability in case of injury unless compliant to basic laser safety procedures.	Safety without hindrance to process or productivity Consider Production or "just demonstration"?
PATH 1	Product Class I depends on Integral Eng'g features of the product Class I is required unless you can justify higher Class.	Product Class I makes OSHA/ANSI easier (Concern only for Service Operations)	Class I exempt from many user requirements	Reduced (Product Class I means "No Hazard" during operation)	Class I may be achievable without interference to the process, but may require solutions, testing and other complexities (time, schedule and budget risks)
PATH 2	Class IV, with safety features added by Procedure or Personal Protective Equipment (PPE), is a legitimate option	SOP and PPE to apply to all functions (Operation, Maintenance, and Service)	Additional location specific requirements for safe use of Class 4 products	Increased risk to workers and observers with open beam accessible	PPE for all in vicinity (many meters out for XX kW Fiber Laser)

Table C-7. Summary Table – Demonstration Candidate Solutions

Demonstration	Description
Class I	a) Contact Shroud rides inside, tower tube rotates b) Cover ends of tower as cap c) Integral interlocks such that all elements are sensed to be in place before laser emission
Class IV	Build a 4-walled room, TLCA (Temporary Laser Control Area) exclude persons from within (unless well protected by other means) Write Demonstration SOP, appoint officers & guards, etc.

Table C-8. Summary Table – Production Safety Solutions

Production	Description
Class I	a) see Class I, above
Class IV	Permanent LCA "Room" (with no humans inside), all workers wear PPE, etc. Write larger SOP with permanent appointments of Laser Safety Officers, etc. Implement formal training programs, conform with ANSI Z 136

1.4 Task 2 – Demonstration: Sub-Scale Long Seam HLAW for Tower Components in Lab Environment

The goal behind GE's participation in a welding development program with NCMS was to demonstrate GE's laser assisted welding procedures in a lab environment. These efforts were focused on process validation prior to conducting a factory demonstration. To ensure the lab based trials were representative of factory welding conditions efforts were made wherever possible to use configurations, materials, and process that are consistent with existing fabrication processes.

1.4.1 Welding System Construction

GEGR constructed a dedicated welding system for this effort. The system was designed to utilize a 14' beam and carriage motion system to carry the welding process head across the sample to be welded (Figure C-3). The vision and motivation behind the selection of this approach was twofold. First, a beam and carriage system provides an economical method of enabling large travel distances for heavy loads. Second, beam and carriage systems closely represent in form, function, and performance attributes of column and boom systems frequently used in tower fabrication. Also the lab demonstration would allow GE to design and validate a welding process head for beam and carriage operation. Allowing for relatively easy transition to production.

Figure C-3. Welding Equipment and Process Heads Mounted to Pandjaris Beam and Carriage System

1.4.2 Material Sourcing

A typical GE 1.5MW 80m tower structure utilizes A572-Grade50 structural steel in thicknesses ranging from 11mm to 22mm. A typical GE 1.6MW 100m tower structure utilizes A572-Grade 50 structural steel in thicknesses ranging from 12mm to 36mm. In an effort to address and validate welding processes for the largest possible range of land-based wind towers produced by GE this effort attempted to demonstrate welding on material thicknesses spanning the 11mm – 36mm range. Sourcing small lots of metric thickness, tower grade, A572G50 was challenging. In the end some material was sourced directly from SSAB (a supplier of GE tower steel), and the remaining material was sourced from a GE tower supplier. Coupon lengths for samples were selected to be 2' for setup and 5' for test and process

characterization. Table C-9 summarizes the material thickness sourced, the number of assembled joints, and the coupon purpose.

1.4.3 Test Plate Assembly

The quality and methods of preparation of joints used for the laser process validation were representative of those used in existing tower fabrication. This was done to maximize the economic benefit of the HLAW process. If more expensive processes were required upstream and downstream of the joining operations to make laser welding operations successful the overall process cost advantage would be reduced.

Because of these factors, test coupons were prepared using conventional tower welding techniques such as oxy fuel cutting or plasma cutting.

Joint design for the welded assemblies varied by thickness, but the general approach employed a double V-groove. A land thickness of 15mm was utilized for all thicknesses (Figure C-4).

To assess the laser joining processes ability to handle the gap and mismatch seen in tower production, test plates were assembled with designed gap and mismatch levels. Table C-10 illustrates the tested configurations.

Production tower segments are tack welded to properly align components before welding. Since tack welds can influence weld quality and have an impact on process stability, it is important to evaluate and document these effects for the HLAW process. To validate the impact of tacking on the weld quality, all test samples were sourced from a GE tower supplier and utilized tacking procedure consistent with existing production (Figures C-5 and C-6).

Table C-9. Material Sourced for Setup and Testing

Shipping ID	Inscribed plates ID	Thickness (mm)	Welded Quantity	Purpose
P001	P001	12	5	Setup
P002	P002	19	5	Setup
P003	P003	30	5	Setup
P004	P004	12	14	Testing
P005	P006	16	14	Testing
P006	P009	22	14	Testing
P007	P011	26	14	Testing
P008	P016	35	14	Testing

Figure C-4. Representative Joint Geometry for Plates Welded

Table C-10. Example of Gap and Mismatch Plate Conditions

Assembly	Gap (mm)	Mismatch (mm)
P004G0.00M0-1	0	0
P004G0.25M0-2	0.25	
P004G0.50M0-3	0.5	
P004G0.75M0-4	0.75	
P004G1.00M0-5	1	
P004G0.00M1-6	0	1
P004G0.25M1-7	0.25	
P004G0.50M1-8	0.5	
P004G0.50M1-9	0.5	
P004G0.75M1-10	0.75	
P004G1.00M1-11	1	2
P004G0.25M2-12	0.25	
P004G0.50M2-13	0.5	
P004G0.75M2-14	0.75

Figure C-5. Test Plates of Various Thicknesses Assembled for Welding

Figure C-6. Tack Welds on Assembled Test Plates

1.4.4 Process Demonstration

Welding processes were demonstrated using GE proprietary procedures in the welding sequences described above.

1.5 Task 3 – Properties and Characterization: HLAW Test Panel Mechanical and NDE

The final task for this project was to evaluate the weld quality of the HLAW joined samples produced in Task 2. Testing methods, conditions, and evaluation criteria were dictated by existing GE win tower fabrication specifications.

1.5.1 Task 3.1 – NDE

As part of the hybrid laser welding technology development program being conducted at the GEGR, each of the samples manufactured were non-destructively inspected. The wind tower weldments must comply with the specification GE Specification P14A-AL-0223. These inspections were accomplished using an ultrasonic technique in accordance with the requirements of AWS D1.1 for cyclically loaded, non-tubular structures. Each acceptable/rejectable area was identified in accordance with the previously cited specifications.

The inspection techniques applied were as follows:

1. AWS 2 MHz, 70° shear wave inspection (AWS D1.1 requirement)
2. 2 MHz, 1" straight beam of parent material adjacent to the weld inspection (AWS D1.1 requirement)
3. 4 MHz, 70° shear wave inspection
4. 5 MHz phased array inspection using a 45-70° sector scan
5. 2 MHz, 1" straight beam through the weld.

The reference level was established using Method 1. The acceptance criteria used was as per the same.

Using the methods mentioned above, areas of acceptable weldments were marked on each plate, from where the mechanical testing and metallurgy characterization specimens were prepared.

Figure C-7 compares the percentage of weld length with NDT defect percentages as function of plate thickness and gap size. NDT defects caused by laser welding process, either lack of fusion or cracking, were observed with gap sizes larger than 0.5mm. These results were

confirmed with cross-section metallurgy. The majority of laser welding defects (~4.3% of total welding) occurred when the gap size is equal to or larger than 0.5mm. Because of this we may recommend 0.5mm as the threshold of the gap size to ensure quality. Another important observation from Figure C-7 is that the defects caused by the SAW process, which accounted for 6.0% of total length, only occurred in the 35mm plates, with no dependence on gap size or the mismatch. Cross-section metallurgy in these areas illustrates that the defects are caused by cracking issues. This indicated that the SAW process was not properly optimized to fill the deep grooves in the 35mm plate with a single pass. In addition, some of the defects caused by non-process issues, such as the delamination of the plates (labeled as Base in Figure C-7) and defects in tacking materials (labeled as Prep in Figure C-7), have been occasionally detected by NDT occasionally in all conditions.

1.5.2 Task 3.2 – Tensile Property Testing

All weld plates were sent to Westmoreland Mechanical Testing & Research, Inc. (Pittsburgh, PA, <http://www.wmtr.com>) for mechanical property testing and microstructural analysis. Locations which passed the NDT were

Figure C-7. Summary of NDT Defect Percentages as Functions of (a) Gap Size and (b) Plate Thickness

marked on the plates, and testing specimens for tensile, impact, hardness, and macro cross-section were cut from the transverse section of the weld joints (as shown in Figure C-8). Three groups of testing specimens were prepared per weld plate in order to lower the measurement variability.

All tensile tests were performed based on the requirements in ASTM E8. To evaluate the tensile properties of the weld joints, button head cylindrical specimens of 0.64" gauge length and 0.16" gauge diameter were machined from transverse section of weld joints. The detailed geometry of the tensile testing bars is shown in Figure C-9 per GE specifications.

The tensile tests were carried out in the room temperature employing a nominal strain rate of 0.005 min^{-1} until the specimens reached the UTS. Figure C-10 exhibits a typical example of stress-strain curve obtained during the tensile tests. The values of the 0.2% yield strength, ultimate tensile strength (UTS), and elongation at four different conditions are reported.

Figures C-11 and C-12 summarize the yield strength and ultimate tensile strength (UTS) of weld joints for plates with different gap sizes and thicknesses. Tower welds are required to have transverse weld tensile strength in excess of 51.5 ksi per GE Energy specifications, and all test weld joints met this requirement. The overall average values of the yield strength and UTS are 60.0 ± 4.0 ksi and 76.3 ± 6.7 ksi, separately. In addition, it was observed that variations in plate thickness, mismatch, and the gap size did not significantly impact the tensile properties of the weld joints. Indicating that the strength of the weld joints is mainly depended on the HLAW and SAW process, which are quite similar for all the plate geometries.

Figure C-8. A Group of Testing Specimens (Tensile, Impact, Hardness and Macro Cross-Section) Cut from the Selected Areas Passing NDT Inspection

Figure C-9. Sketch of Tensile Specimen Bar Per GE Specifications

Figure C-10. Sketch of Tensile Specimen Bar Per GE Specifications

Figure C-11. Summary of Yield Strength and UTS of Weld Joints with Different Plate Thicknesses and Gap

Figure C-12. Summary of Yield Strength and UTS of Weld Joints for the Plate of 26mm with Different Mismatch and Gap Sizes

1.5.3 Task 3.3 – Impact Property Testing

Impact test has been carried out on Charpy V-notch specimens. All impact tests were performed based on the requirements in ASTM E23. Standard specimens with the dimensions shown in Figure C-13 were cut from transverse section of the joints. The V-notch with depth of 0.08" from the top of the face, included angle of 45°, and root radius of 0.01" was made in the center of the weld joints. The impact tests were conducted at -40°F. Impact tests were carried out on a standard Charpy specimen.

Figure C-14 illustrates the plots of absorbed energy for Charpy impact tests at -40°F. Although the data are highly scattered for the HLAW-SAW joints, performance of all testing samples exceed 20 ft-lbs, which is the tower welding qualification requirement.

Figure C-13. Sketch of Charpy Specimen Bar Per GE Specifications

1.5.4 Task 3.4 – Hardness Testing

All hardness tests were performed based on the requirements in ASTM E384. Vicker hardness tests were carried out with an applied load of 10kg (HV10). As shown in Figure C-15, hardness measurements were made at 1mm away from the top and bottom surfaces of the weld plates, as well as the center of the laser weld zone and the HAZ. In addition, hardness measurements were taken in the base material at least 0.5" far away from the laser and SAW HAZs.

Figure C-14. Summary of Carpy Impact Testing Results at -40°F: (a) Effects of the Plate Thicknesses and Gap Sizes; (b) Effects of Mismatch and Gap Sizes for the 26mm Thick Plate Welding

Figure C-15. Hardness (HV10) Testing Plan Per Cross-Section Mount

All individual hardness measurements in weld zones and HAZs are higher than the base materials (HV10 153.8 ± 6.5) but below the HV10 320 limit defined by GE wind tower welding specifications. Figures C-16 and C-17 compare the maximum hardness measurements in weld regions as well as in the HAZ for different plate thicknesses, mismatches, and gap

sizes. It is clear that mismatch and gap size have little effect to the hardness. However, it is found that the hardness values for both weld and HAZ are increased with the plate thickness when it is below 26mm. This is because for the plates thinner than 26mm, the HLAW and SAW processing conditions are quite close, resulting in a similar level of heat input and tempering. For thick plates, higher cooling rates were achieved as heat dissipates more quickly in the larger thermal mass. This leads to finer microstructures in the weld joints and the surrounding HAZ. This explains the increase of hardness values when the plates of 12mm, 16mm, and 22mm are compared. For plates thicker than 22mm, SAW processing conditions have been modified, with heat and wire feed increased, to fill the deep grooves within one pass. The heat input will temper the weld joints and the HAZ, and eventually lower the hardness values.

Figure 16. Maximum Hardness (HV10) and Weld (right) and HAZ (left) for the Plate of 16mm at Different Conditions

Figure C-17. Maximum Hardness (HV10) of Weld and HAZ for the Plate of 16mm at Different Conditions

1.5.5 Task 3.5 – Cross-Section Metallurgy Characterization

The metallographic specimens have been prepared by mechanical polishing, followed by etching with 5% Nital. Figure C-18 shows the weld and HAZ macrostructure for all different plate thicknesses. As can be seen in the transverse section for each condition, a full penetration weld was achieved using one pass SAW from each side of the plate following the one-pass HLAW process. Typical microstructures revealed columnar grains resulting from the welding process. The transverse sections show no obvious discontinuities or defects existing in the weld pool and the weld microstructure is fairly uniform.

The cross-sectional metallographic specimens were also prepared from regions rejected by NDT. Figure C-19 summarizes several typical defects observed within the weld joints. Figure C-19a shows lack of fusion during HLAW

process. This has been widely observed for the gap size of 0.75mm or larger, which is too wide to be consistently welded with the HLAW process. Figure C-19b shows the cracking phenomenon in laser welding zone, which occurs occasionally (especially for wide gap and large mismatch). These cracks occur partly as a result of hot cracking during fusion welding due to the solidification shrinkage. Figure C-19c illustrates a discontinuity defect caused by tack material, which may be existing initially, but remain after the welding process due to the insufficient penetration of SAW. Another cracking phenomenon shown in Figure C-19d was only observed in the SAW regions for the plate of 35mm thick. As mentioned previously, the SAW travel speed for the plate of 35mm has been reduced to 760mm/min to cap the deep grooves within a single pass. The high deposition rate, puddle size, and residual thermal stresses produced at this condition increased the cracking tendency in the SAW regions.

Figure C-18. Cross-Sectional Morphologies of Weld Joints at Different Plate Thicknesses

Figure C-19. Various Defects Observed Within the Weld Joints: (a) Lack of Fusion in Laser Weld Zone; (b) Cracking in Laser Weld Zone; (c) Defects Caused by Tack Material; (d) Cracking in the SAW Zone

1.6 Conclusions

Based on this study the following conclusions can be made:

- This body of work was able to validate a successful approach for laser assisted welding of wind tower components.
- The processes performed demonstrated the ability to meet all of the key mechanical property requirements for GE wind towers.
- Weld quality is closely correlated to the gap of the assembled joint. To keep weld quality sufficiently high, the gap should be limited to 0.5mm or less for all assemblies.
- Assessment of the economic benefit of laser assisted processes was also validated. Laser assisted processes demonstrated the ability to deliver substantial reductions in welding consumables and cycle time when compared to conventional SAW.

By developing the advanced manufacturing technology required to improve domestic manufacturing capacity and productivity, this team's efforts will directly contribute to the following benefits:

- Provide a technological lead for the U.S. in advanced energy technologies by improving productivity and reducing manufacturing costs for wind towers.
- Enable reductions of imported energy.

- Drive reductions in energy-related emissions.

Productivity comparisons were made between processes typically used in tower production and the processes demonstrated in this study. As mentioned before the primary benefits of the laser assisted tower welding approach resides in the processes ability to reduce the amount of welding consumables and time required to weld tower sections. The dollar value of these impacts is dependent on the existing process efficiency, the laser process configuration, and the welded length and thickness. It is possible to look at these benefits in a more generic manner by examining fractional improvements. Figure C-20 give representative values by thickness for the weld metal and cycle time reduction attainable by moving from conventional to laser assisted tower welding.

Based on internal GE calculations that have been validated by data provided by GE's wind tower suppliers, the welding productivity that is obtained by switching from conventional SAW to laser assisted welding is a 2X to 4X for a standard tower.

Capital equipment costs for the laser process components used in this study range from approximately \$1M to \$2M USD. The relatively high capital cost of the welding equipment necessitates careful application and site selection to enable appropriate ROI.

Figure C-20. Representative Weld Metal and Cycle Time Reduction in Moving From SAW Only to Laser Assisted Welding

1.7 Recommendations

At the completion of this project the laser assisted tower welding technology has been demonstrated in a laboratory environment placing the Manufacturing Readiness Level (MRL) at 5. The next milestone and technical hurdle to clear as part of the technology development effort would be to demonstrate this same welding performance in a factory environment.

This demonstration should take place at an existing wind tower supplier and the work scope should include both circumferential and longitudinal welding of tower components. This exercise would validate the welding performance and quality on tower scale structures and serve as a final technical validation for the laser assisted welding processes. In addition, over the course of this type of exercise the durability of laser welding equipment in a tower fabrication environment could be documented.

Successful completion of a demonstration of this type would be a natural segue to technology implementation and low rate production.

While this type of activity could have been easily justified in the years from 2008 – 2012, 2013 brings increased uncertainty in the wind market due to low natural gas prices and the passing of the production tax credit. Because of this uncertainty tower suppliers are hesitant to look at investing in productivity tools.

1.8 References

- [1] EERE (U.S. DOE Office of Energy Efficiency and Renewable Energy). 2009. *20% Wind Energy by 2030 Increasing Wind Energy's Contribution to U.S. Electricity Supply*. DOE/GO-102008-2567. Oak Ridge, TN: pg 203.
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