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Low Wind Speed Turbine Development Project Report

November 4, 2002 – December 31, 2006

A. Mikhail
Clipper Windpower, Inc.
Carpinteria, California

Subcontract Report
NREL/SR-500-43743
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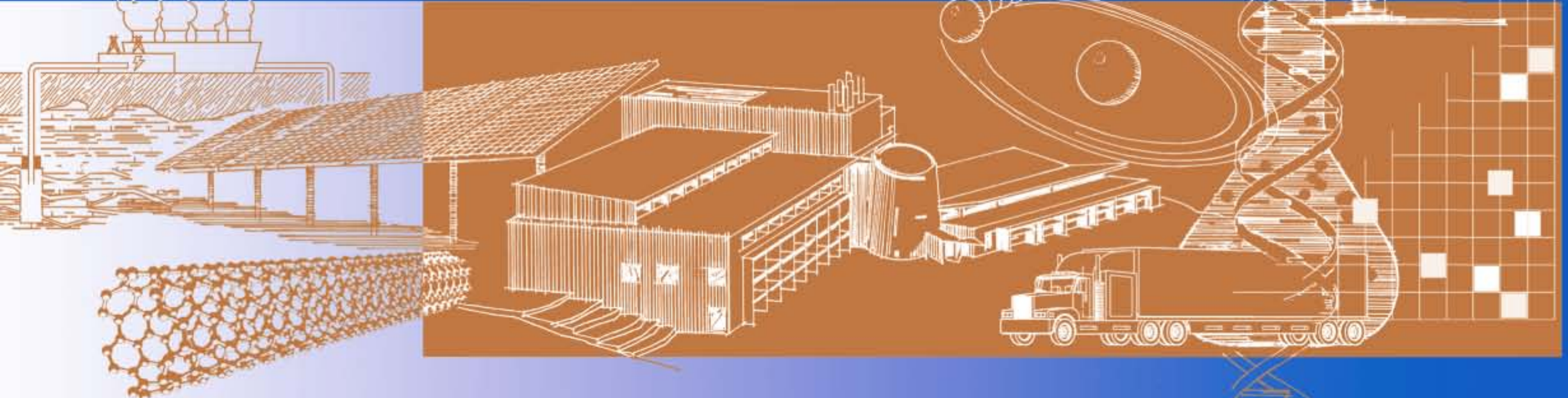

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NREL Technical Monitor: S. Schreck

Prepared under Subcontract No. ZAM-3-31235-06

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Foreword

This final report describes the work performed by Clipper Windpower, Inc., for the Low Wind Speed Turbine Development Project (2002–2006). The overview text was assembled by PWT Communications with significant contributions from Clipper Windpower engineering staff and consultants. This report draws upon other detailed proprietary reports created by Clipper Windpower engineering staff, consultants, and certification and testing organizations including Germanischer Lloyd WindEnergie GmbH (GL) and the National Renewable Energy Laboratory (NREL).

Acknowledgments

The Clipper Windpower team includes: Amir Mikhai, Senior Vice President of Engineering; Derek Petch, LWST Project Manager (dpetch@clipperwind.com); Megan McCluer, Project Manager for LWST Final Report. Significant contributions also were made by other Clipper personnel, particularly Kevin Cousineau, Tom Nemila, Brian Glenn, Zachary Markey, and Rahul Yarala.

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List of Acronyms and Abbreviations

AC	Alternating current
Adams	Automated design mechanical systems design tool (MSC Software)
AEP	Annual energy production
AOE	Annual operating expenses
C89	Clipper 89-m blade
C93	Clipper 93-m blade
C96	Clipper 96-m blade
CEC	California Energy Commission
CNC	Computer numerical control
COE	Cost of energy
CSIM	Clipper simulation (a model used in control system development)
CVAR	Clipper distributed static VAR correction system
DC	Direct current
DGD	Bench-scale Distributed Generation Drive (DGD)
DGD1	1.5-MW Distributed Generation Drive 1; 2nd generation 1.5-MW with eight 650-kW generators
DGD4	2.5-MW Distributed Generation Drive 4 Quantum Drive; Liberty 2.5-MW drivetrain final version
DOE	U.S. Department of Energy
DSVC	Distributed static VAR correction
EPU	Emergency power units
ERB	Extendable rotor blade system
FEM	Finite element model
FERC	U.S. Federal Energy Regulatory Commission
GCU	Generator control unit
GE	General Electric Wind
GL	Germanischer Lloyd WindEnergie GmbH
GUI	Graphical user interface
IBPC	Individual blade pitch control
IGBT	Integrated gate bipolar transistor
jib crane	Two-metric-ton jib crane used for the complete assembly
LSS	Low-speed shaft
LVRT	Low-voltage ride-through
LWST	Low wind speed turbine
NREL	National Renewable Energy Laboratory
NWTC	National Wind Technology Center
O&M	Operations and maintenance
PCU	Pitch control unit
PE	Power electronics
PI	Proportional-integral controller (a generic control loop feedback mechanism)
PID	Proportional-integral-derivative controller
PM	Permanent magnet
PROPID	Prop ID design tool
PSD	Power spectral density, or power semiconductor device

RBR	Retractable rotor blade
SCADA	Supervisory control and data-acquisition system
SCR	Silicon-controlled rectifier
SCR-T	Silicon-controlled rectifier transformer
SMUD	Sacramento Municipal Utility District
SPL	Sound pressure level
SPM	Salient pole permanent magnet generator
TCU	Turbine-control unit
TEWAC	Totally enclosed water-to-air cooled
TEWC	Totally enclosed water-cooled
TPSS	Turbine protection and safety system
TSR	Tip speed ratio
VAR	Volt-ampere reactive
VDAS	Virtual data-acquisition system
WT_Perf	performance prediction code (National Wind Technology Center)

Executive Summary

This report documents the technical results of the Low Wind Speed Turbine (LWST) Development Project. This project was funded jointly by Clipper Windpower, Inc. (Clipper) and the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL), through Subcontract Number NREL/ZAM-3-31235-06.

The goal of the LWST project was to engineer, fabricate, and test a wind turbine that can produce electricity at competitive cost of energy (COE) in low wind speed regions in the United States. The low wind speed sites targeted by this effort have annual average wind speeds of 5.8 m/s (13.0 mph), measured at 10 m (32.8 ft) hub height. Founded on a portfolio of technologies that promise to reduce the COE in DOE Class-4 wind sites (IEC Class 3), this new competitive wind technology could result in 35 GW to 45 GW of additional wind capacity by 2020 at these plentiful low wind speed sites.

The four-year development and testing effort was founded on the NREL findings published in the WindPACT and Next Generation Turbine studies. It was built on research and development efforts that had been underway since 1998, including the Distributed Generation Drive (DGD) project which was funded in part by the California Energy Commission (CEC) and NREL.

The development of the turbine proceeded at a rapid pace. In 2003, the design work was well underway. In 2004, the prototype was constructed. In 2005, erection and testing of the prototype provided information to fine-tune the design. In 2006, certification and commercial sales of the Liberty turbine series were accomplished. In 2007, Clipper received the DOE Wind Energy Program Outstanding Research and Development Partnership award for its work with DOE and NREL to advance U.S. wind-turbine development.

The first phase of the LWST project included completion of the design and construction of a prototype 1.5-MW DGD1 drivetrain that used 8 generators. The new design improved the efficiency, reduced the number of components, and reduced the weight of the wind-turbine DGD drivetrain assembly. Tests of this full-scale prototype demonstrated the load-reducing effect of using multiple subdrivetrains (small generators and gearboxes) driven through a load-splitting first stage.

The second phase of the LWST project consisted of completing design and trade-off studies and then constructing and testing the DGD4 Quantum Drive, which used four generators. Extensive design documentation was prepared and submitted to the Germanischer Lloyd WindEnergie GmbH (GL) certification organization.

The third phase of the LWST development project included fabricating a prototype turbine—the 2.5-MW Liberty C93—and installing it at the NREL field-test site in Medicine Bow, Wyoming. The turbine testing began in April 2005 and was completed on June 30, 2006. NREL personnel completed tests for noise, loads, power performance, and power quality. The tests resulted in several key "lessons learned," and identified design improvements that subsequently were incorporated.

On March 6, 2005, GL certified the C93, an upwind, horizontal-axis, 3-bladed, variable-speed, 2.5-MW wind turbine. The C93 has a 93-m (305-ft) rotor mounted on an 80-m (262-ft) tower. On March 7, 2006, GL issued design certification for two more Liberty configurations, 89 m (202 ft) and 96 m (315 ft).

The certification, manufacture, and installation of the Liberty turbine series are the direct result of the LWST development project. The C93 is certified for a 30-year design life, and the C89 and C96 each are certified for a 20-year design life and for operation in extreme cold-climate conditions. The achievement marks the first large wind turbine greater than 2 MW to receive the new GL extreme-temperature certification. As of November 2007, Clipper had firm orders for 1,530 MW (612 units) and contingent orders and joint development/contingent sale agreements for about 4,000 MW to be installed in the United States by 2010.

Table of Contents

Introduction and Project Overview

This report summarizes work completed on the Low Wind Speed Turbine (LWST) project. The project was jointly funded and completed by Clipper Windpower, Inc. (Clipper) and the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) through Subcontract Number ZAM-3-31235-06.

Project Background

In 2002, the DOE Wind Energy Research Program began a new effort to develop wind technology that would enable wind-turbine systems to compete with conventional energy sources in regions having low wind speeds. The sites targeted by this effort have annual average wind speeds of 5.8 m/s (13.0 mph), as measured at 10 m (32.8 ft) hub height. Such sites are abundant in the United States, and new technology could exploit them it would increase by twenty fold the available land area that could be economically developed for wind power generation.

The DOE set a goal to develop low wind speed technology and achieve a levelized cost of energy (COE) of $0.03/kWh (2002 dollars) at these sites by 2010. A three-phase technology development approach was proposed: (1) concept design, (2) component development, and (3) system development and testing. This approach built upon previous activities undertaken in the WindPACT and Next Generation Turbine programs (Deane and Howes 2002; Ellis and Eisenhauer 2002; Global Energy Concepts LLC 2001; Griffin 2000; Poore and Lettenmaier 2003; Shafer 2001; Smith 2001). The LWST project was awarded to Clipper in November 2002 under the DOE development effort, and administered by NREL as a cost-shared activity that included the three elements of the LWST technology development approach. Clipper conducted detailed concept studies of components and systems, developed components based on these certified designs, and developed an innovative wind-turbine prototype for manufacture and testing.

Prior to proposing the LWST work to DOE, Clipper developed wind farms using General Electric Energy (GE) turbines. The gearboxes in the GE turbines were heavy and costly, therefore Clipper and its subcontractors explored the idea of a gearbox that split the loads among several generators. The first concept explored was to use eight generators (this original work was funded by the California Energy Commission (CEC)). A bench-scale model was built, and the initial load measurements supported the idea. The original goal was to develop a drivetrain that would fit on the GE 1.5-MW turbine.

After the initial work for the CEC, Clipper assembled an experienced design team and in March 2002 submitted a proposal to NREL for developing innovative components and integrating them into a Low Wind Speed Turbine for DOE Class-4 wind sites (low wind speed sites) (IEC Class 3). The contract was awarded to Clipper in November 2002.

The work under this contract proceeded in three phases. Phase I of the LWST project (described below), included design studies to improve the efficiency and reduce the weight of the wind-turbine Distributed Generation Drive (DGD) drivetrain assembly. The prototype 1.5-MW DGD1 drivetrain had eight generators. The DGD1 was developed from 2001 to 2003 and was tested for power quality and lifetime at the NREL dynamometer test facility in 2003.

The tests of the 1.5-MW DGD1 prototype drivetrain demonstrated the load-reducing effect of using multiple small generators and gearboxes driven through a load-splitting first stage. Testing the permanent-magnet generators verified their suitability for use in the drivetrain. Responding to lessons learned from testing DGD1, Clipper developed the 2.5-MW Quantum Drive that used four generators, and then completed dynamometer tests of the drivetrain—including gearbox, generators, and converter—at NREL (October 2004 through January 2005).

Phase II of the LWST project (described below) included completion of design studies for the Clipper Liberty 2.5-MW Wind Turbine. In March 2006, Germanischer Lloyd WindEnergie GmbH (GL) issued design certification that covered 3 rotor diameters of the 2.5-MW platform: 89 m (292 ft) (IEC Class IA), 93 m (305 ft) (IEC Class IIa), and 96 m (315 ft) (IEC Class IIb). The certification process required detailed design documentation and rigorous review.

In Phase III of the LWST development project (which overlapped in time with Phase II), Clipper fabricated a prototype turbine using the drivetrain tested at the NREL dynamometer test facility and installed it at NREL's test site in Medicine Bow, Wyoming. Testing of the Clipper C93 Liberty 2.5-MW turbine (using the Quantum Drive with four generators) began in April 2005 and was completed on June 30, 2006. noise, loads, power performance, and power-quality testing were completed under the direction of NREL personnel. During this testing several key lessons were learned and, in response. the design was improved. Clipper's work under the LWST project contract ended on December 30, 2006.

This collaborative program resulted in the Clipper Liberty series of 2.5-MW wind turbines, which have been certified by GL. The Liberty is the first wind turbine greater than 2 MW to receive the new GL extreme temperature certification. Commercialization of the Liberty turbine series (C89, C93, C96, C99) is described below.

General Product Objectives

The objective in this cost-shared design and development effort was to develop a prototype turbine having a good possibility of achieving the DOE COE goal of $0.03/kWh at Class-4 wind sites by 2010. The approach used to achieve this goal was to produce technology innovations that reduce the capital cost of the turbine, increase energy capture and productivity, increase reliability, and reduce the turbine's operation and maintenance costs.

Design Philosophy and Approach

Recognizing that no single innovation can extend the application of turbines into the low wind speed class, the Liberty series of low wind speed turbines is designed around a state-of-the-art suite of optimizations that covers all aspects of low wind speed energy production. This approach facilitated the design of techniques and algorithms that simultaneously could mitigate loads, reduce vibrations, increase annual energy production (AEP), and reduce COE. The control system was envisioned and implemented as an easily programmable microprocessor embedded in the turbine-control unit. It supervises an individual blade-pitch rotor and the novel multi-generator drivetrain optimized for variable-speed operation. The gearbox that was designed and tested mitigates gearbox loads through load splitting, extends the range of operational speeds, and enhances energy capture.

Installation and maintenance costs are a significant component of COE, therefore Clipper set the goal of optimizing the design of the mechanics. Optimizations include reductions in down-tower cable cost through intelligent relocation of all electric components, the use of advanced embedded control systems where needed, and the development of wire-harness manufacturing techniques that reduce the cost below those for off-the-shelf control systems. Wherever possible weight has been minimized through innovations such as the distributed drivetrain, variable-speed operation, and the advanced control system. This reduces installation costs by lowering transportation costs and allowing the use of a smaller crane for installation. Over time, the cost of maintenance is reduced by the design and use of an onboard jib crane located in the nacelle that can be used for servicing most of the components in the nacelle.

Result of Contract

A result of the contract is that an array of innovative technologies in the Liberty turbine was designed to improve performance in low wind speeds and provide the lowest COE possible. The following features and components are included.

- The DGD drivetrain, the 2.5-MW DGD4 Quantum Drive, with four synchronous, permanent-magnet 660-kW generators. In addition to mitigating gearbox stresses, reducing the number of components, reducing the weight, and reducing system loads (costs), the DGD4 Quantum Drive multiple generators permit continuous operation even in the event of a generator outage, thus increasing annual energy capture and reducing COE.
- The high-efficiency MegaFlux permanent-magnet generator.
- Variable-speed operation.
- The multi-function controller operating in an embedded power PC.
- Optimized system operations to increase energy capture, reduce loads, and extend component life. For example, the generator control algorithm enables a wide range in variable rotor speed, improving turbine aerodynamic efficiency by adjusting to ever-changing wind velocities, operating at a constant tip speed ratio, and briefly storing and releasing energy from wind gusts while also reducing torque spikes. Turbine-condition monitoring allows real-time system protection: blade strain measurement, gearbox oil analysis, bearing temperatures, vibration monitoring, and hydraulic system pressures.
- The power converter with 4 690-VAC, voltage-sourced, insulated gate bipolar transistor (IGBT)-based, 6-pulse inverters. Power is delivered exclusively from each generator’s stator and is rectified to DC. Then IGBT technology is used to convert the DC power to AC current. This approach extends generator life, thus reducing COE. Low-voltage ride-through capabilities of this design exceed industry standards and enable the turbine to stay online during low-voltage events (to 10% of the applied utility-grid nominal values).
- The onboard, two-ton jib crane located within the nacelle provides easy access to generators, yaw drives, drivetrain components, and service brakes. Quick repairs reduce both operations and maintenance (O&M) costs and downtime.
- The nacelle was designed for aesthetic appeal and service access. Features include power roll-down door at the rear, hub access from interior, and external heat rejection.

- The reduced system weight and modularity decreases transportation costs and enables installation of a 2.5-MW turbine with a crane that is sized for most commercial 1.5-MW units.

Project Lessons Learned

The LWST contract allowed for quick development of the Liberty turbine series. The cost-shared contract moved the concept of a distributed drivetrain incorporated into a wind turbine with a sophisticated control system to a commercial product in record time—about four years.

Testing the subsystems, both at NREL's National Wind Technology Center and at Clipper suppliers, validated innovative design features and identified design weaknesses to be remedied. Initial tests of the DGD1 drivetrain with eight generators, for example, provided insights for the design and application of the DGD4 Quantum Drive with four generators. Prototype testing of the C93 Liberty turbine at Medicine Bow, Wyoming, demonstrated system designs and allowed fine-tuning of the complex control algorithms needed to take full advantage of the load reduction, cost savings, and increased energy capture of the system. Cooperative programs encouraged a rigorous design approach through constructive input, due-diligence reviews, thorough testing, and complete documentation.

Contributors to Reduced Cost of Energy

Clipper has leveraged several efficiency improvements to reduce COE. The use of multiple generators helps in a number of ways. With respect to installation, maintenance, and service costs, the use of four compact permanent-magnet generators (1,814 kg (4,000 lb) each) instead of one monolithic generator eases transportation and means that each generator can be handled with the two-ton jib crane inside the nacelle. This saves time and expense in component replacement or maintenance. Although the initial installation of the turbine does require an external crane, the lighter weight and increased modularity of the Liberty 2.5-MW turbines enable installation using cranes that generally are sized for commercial turbines of 1.5 MW or less.

The multiple-generator design also can reduce total downtime. Splitting the load off the bull gear by a factor of eight helped to extend the fatigue life to 30 years (C93). Most commercial turbines are rated for 20 years. Further, the Liberty turbines can operate using only two or three of the four generators—albeit with a reduced power rating. Other features that contribute to lowering COE include greater drivetrain efficiency than that of most turbines, component modularity, nacelle access to the hub, and a patented technology that isolates the turbine from grid disturbances and allows a unity power factor down to 5% of rated power.

The COE and AEP are improved by the turbine's low cut-in speed of 4.5 m/s (10 mph), the increased energy capture via sophisticated control of the individually pitched blades, and the use of blade pitch to attenuate tower and advanced torque-control algorithms to reduce drivetrain vibrations.

Liberty Turbine Product Description

The initial commercial product, the Liberty turbine, incorporates many of the demonstrated features developed during the LWST development project. Liberty turbines are built around a state-space embedded-microprocessor controller that takes full advantage of its individual blade pitch control (IBPC), four-generator drivetrain, and patented Clipper unidirectional power flow variable-speed technology that allows full isolation from the grid. Using IBPC and appropriate sensor feedback the controller not only is able to optimize energy capture, it also dampens harmonic vibrations of the tower.

The Liberty turbines feature the Quantum Distributed Generation Drivetrain (Quantum Drive). The Quantum Drive features four high-speed output shafts, it is lighter and more efficient than other commercial gearboxes, and splits the torque by a factor of eight at each stage. The Quantum Drive uses two stages—versus the three used in commercially available gearboxes—which results in increased efficiency. Additionally, the modularity of components results in the ability to replace many high-speed stage components using the onboard two-ton jib crane.

The heart of power production is the MegaFlux permanent-magnet generator. These generators are very compact, measuring 1.07 m × 0.91 m (3.5 ft × 3.0 ft), and do not require a torque-limiting coupling between the gearbox and the generators because of low short-circuit current. These generators feature greater efficiencies in all operational loads than those of doubly fed or wound-field synchronous generators. In regions where contaminated air is a problem, a totally enclosed water-to-air-cooled (TEWAC) generator is an option. For applications in less-demanding environments, an IP54 air-cooled option is available; this option provides the standard of protection offered by an enclosed junction box against ingress water and dirt. The generators have a form-wound Class-H stator insulation rated for medium voltage and a low weight (less than 1,814 kg (4,000 lb) per generator), and they can be handled by the onboard two-ton jib crane. The Liberty turbine can operate at reduced power output with only three—or even two—generators.

Distributed Generation Drivetrain

The WindPACT turbine-design studies, especially the drivetrain study (Poore and Lettenmaier 2003), provided important background for development of the distributed generation drivetrain (DGD). Cost models provided in these studies showed that the drivetrain was the most expensive component in the baseline turbine system, and that the greatest cost reductions could be achieved by focusing on that area. The preliminary conclusion was that a two-stage gearbox with multiple outputs could lead to reduced gearbox costs. The initial capital cost per kilowatt of an induction-generator system was approximately constant regardless of the number of generators used.

Other studies concluded that the use of a multiple-generator design could decrease the unscheduled maintenance and replacement risk for the turbine. This seemed true even after accounting for four-to-six times as many component faults as would be found in a monolithic drivetrain.

The DGD concept was developed from these studies, and it runs counter to a fundamental rule in mechanical design: that fewer parts and minimal complexity are highly desirable. The studies showed that this assumption is false, however, when the price of failure is extreme. Replacement of a single monolithic gearbox or generator from atop an 80-m (262-ft) tower could cost more than $250,000 (15% to 20% of the installed turbine cost). This could be more than the entire markup a manufacturer could collect from the original sale. The risk of such a replacement cost could be mitigated by the split-load-path approach of the DGD, in which smaller components can be replaced without the use of a large crane.

The multiple-generator design also reduces the gear-tooth loading, because the load path is split at the low-speed end. Gear-tooth loads not only drive initial and life-cycle costs of gearing, they also affect the costs of bearings, shafts, and the gearbox housing. The U.S. Patent Office issued Dehlsen Associates patent protection (U.S. 6,304,002, 31 claims) for this design on October 16, 2001.

DGD Early Design and Feasibility Analysis

The DGD studies covered the gearbox, generators, power converters, and controller. Several design options were assessed, including:

- Salient pole PM (SPM) generators developed under the WindPACT program;
- Stepped variable speed using multi-pole generators, which could add as much as 5.3% to annual energy production without infringing on existing patents;
- Squirrel-cage induction generators with full conversion; and
- Doubly fed induction generators with partial conversion.

In 2001, the research conducted for the WindPACT project investigated controls for a novel gearbox for large-rotor-diameter, high-torque wind turbines and tested a laboratory-scale model. This gearbox—the DGD—consisted of an input shaft-driven bull gear that drove several pinions around its periphery. These pinions divided the input torque load at its highest point, thereby reducing gear-tooth stress, and each pinion drove a small generator. Equipment for this program included a lab-scale gearbox, five 0.5-kW squirrel-cage induction generators, and a small dynamometer (< 5 kW). This equipment was fed with 480-V three-phase AC power, and a sophisticated control and data-acquisition system was added to measure all significant generator characteristics.

The power and control side of the DGD took the mechanical output from the individual second-stage gearboxes and produced three-phase electrical power to the utility line. To perform successfully, this system had to:

- Ensure a uniform torque load distribution between generators;
- Smoothly connect and disconnect with the utility line;
- Seek maximum operating efficiency;
- Monitor and provide protection for mechanical and electrical parameters operating out of specification; and
- Accommodate input from external systems and operators.

The 2001 analysis concluded that construction of a reliable DGD gearbox was feasible and could include readily available parts and materials.

Prototype 1.5-MW DGD1 Drivetrain: Design, Construction, and Testing

After the bench-scale DGD drivetrain was assessed, work proceeded to engineer, fabricate, and test the 1.5-MW prototype DGD1 drive that used eight generators (Figure 1). The full-scale prototype was constructed (Figure 2) and installed with a closed-loop generator field control system at the NREL dynamometer test facility at the National Wind Technology Center (NWTC) near Golden, Colorado. The testing centered on verifying the entire subsystem design, the operating characteristics and design assumptions, and endurance (through duration testing of the gearbox). In late 2002 and early 2003, the gearbox, generators, control system, converter, and rectifier were tested at NREL's dynamometer test facility.

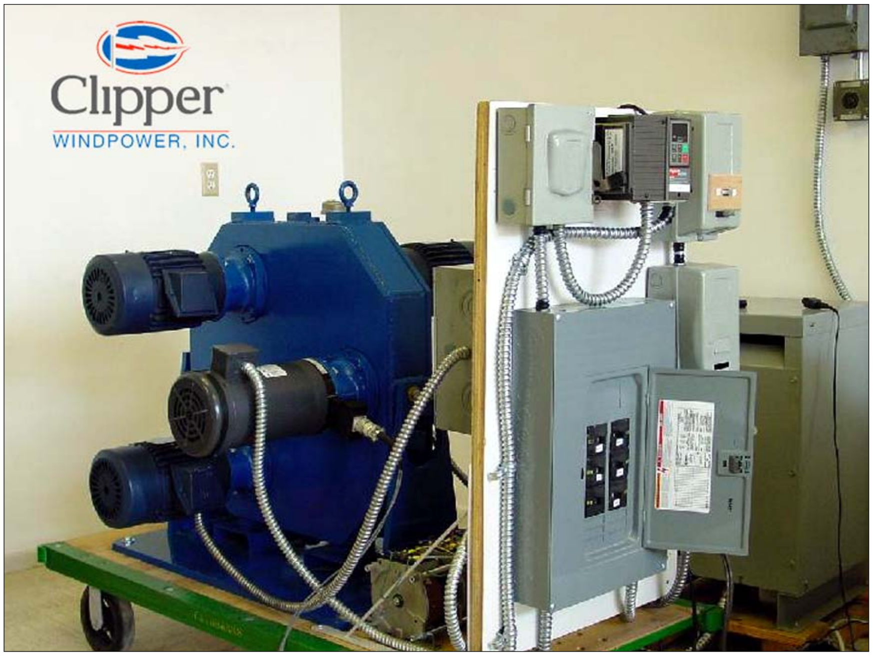

Figure 1. Lab-scale DGD (this test equipment was used in the investigation and development of controls specific to multiple generators)

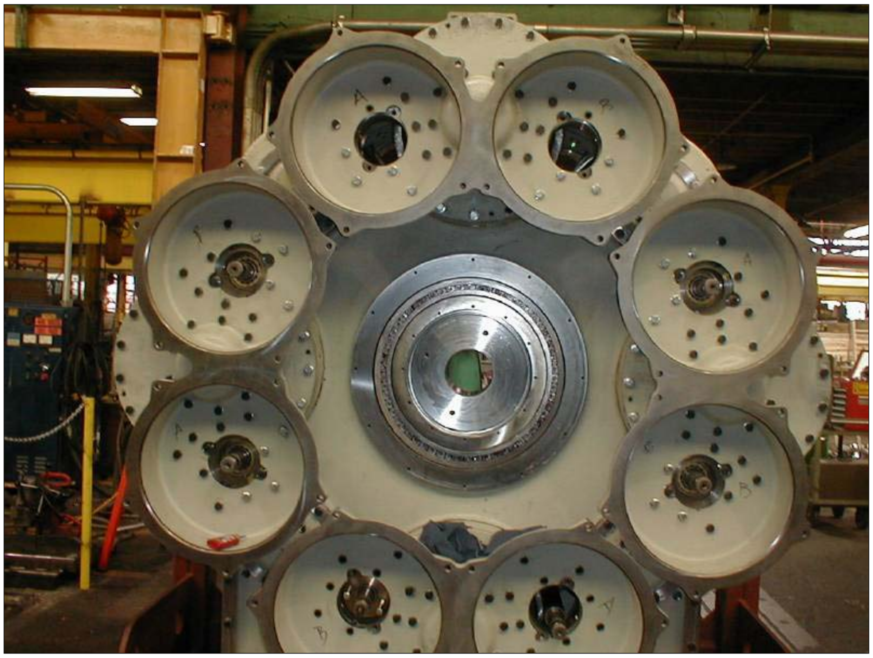

Figure 2. The DGD1 during assembly

Trade Studies

At the beginning of the DGD1 project, design and trade-off studies were conducted for the gearbox, generators, and power electronics. An early gearbox design trade-off study enabled development of a method to optimize a gear train, adapt the configuration (DGD bench scale) to bedplate configurations typical of commercial turbines in the 1.5-MW class, and predict weight and cost based on the number of generators. Designs using fewer generators also were examined to determine the cost impact of generator quantity. The gearing was optimized for weight and cost, including consideration of physical and regulatory constraints. The effect of the number of generators on reliability and estimated repair and maintenance costs also was examined.

Some important trade-offs were considered when comparing permanent-magnet and wound-field synchronous generators. Wound-field synchronous generators require the use of a field regulator, which gives a constant-voltage DC bus and reduces power converter cost as compared with the variable DC bus converter required for a permanent-magnet generator. Permanent-magnet generators also were expected to have higher efficiency than wound-field generators, especially at low speeds. The cost of wound-field synchronous generators, however, was less than the expected cost of permanent-magnet generators. Detailed designs were considered for generator and power electronics together with estimated costs. An additional analysis examined the effect of generator speed on gross annual energy capture.

Test Report Overview for DGD1

The power train final test report includes the following tests and findings.

- Verification—through operational testing—that the field regulators can achieve constant voltage regulation at the output terminals of the generator(s) over a 2:1 speed range and full-load range.

- Connection and operation of the 1.8-MW power electronics conversion system, which feeds the drivetrain, generated three-phase, 575-VAC power into the NREL grid during testing.
- Development and refinement of controls for the management of the power converter modes (run, start, stop, fault, alarm).
- Incremental additions of generator pairs.
- Verification of speed range and the computation of the efficiency of the system and its components.
- Subjection of the gearbox to running loads at 130% of rated load for a total time of 1,600 hours to accomplish accelerated life-span testing.
- Dismantling and inspection of gearbox components at a given running time interval.
- Subjection of the drivetrain to anticipated fault conditions, including loss of phase, over-speed, and electrical (open-circuit) load loss.
- Monitoring of the drivetrain for temperature, vibration, local stress, and acoustic output during various phases of testing.
- Calculation of the operating efficiency of specific drivetrain components and the complete drivetrain.

The 1.5-MW DGD1 ran for about 600 continuous hours. Prior to the continuous run, the gearbox underwent about 200 hours of starting and stopping to complete adjustments of the test setup. The setup used eight 250-kW generators and was assembled at the NWTC (Figure 3). The electrical setup was similar to the final Liberty turbine design: operating the generators, rectifying the power, and inverting the power back to AC.

Figure 3. DGD1 system installed on the NREL dynamometer during testing

The testing provided important insight about how the rectifiers and converters work together at high power levels, and what type of software was needed to control them (for example, to accomplish fast torque control). This learning process greatly accelerated further drivetrain development, and the results were incorporated into the prototype 2.5-MW Liberty turbine.

A key lesson learned was that the drivetrain had torque oscillation. Although this could have been caused by a feedback loop in the control system, that scenario was ruled out during testing at NREL. The problem was identified as drivetrain resonance and was solved through high-speed notch filtering of the torque oscillation signals at the converter. The 1.5-MW DGD1 was run up to full power at NREL for a validation test of the oscillation attenuation strategy. The revised controller successfully damped gearbox and main shaft natural frequency. Regarding gearbox lifetime, the 1.5-MW DGD1 ran at 1.8 MW for 600 hours (overloaded), and this revealed a great deal about the fatigue life of the gearbox.

Other issues were detected during testing and subsequently were resolved. A fan clearance problem was solved by machining. DC exciter failures were solved by rewinding and installing transient voltage suppressor (TVS) components. Main stator failures were solved by reinstalling the cover screens and rewinding. Subsequent stator failures could have been caused by the ingress of contaminants or the rewind of the generators. The small generator size and weight allowed change-outs using the NREL in-house crane, and common construction allowed for easy repair at a local facility.

The converter consisted of four IGBT-based inverters. Good current regulation was maintained throughout the test period. The converter’s fault output drove the safety system without problems. When DC bus voltages were 1,000 VDC or less, there was small problem with matrix temperature. After inductor repair, the converter operated for more than 360 hours without failure at nearly 1.6-MW output power.

Graphical user interface (GUI) problems were solved with new code. The DC bus capacitor failure was solved by using higher-voltage capacitors and a manual field-control system. The AC inductor failure was solved by replacing the inductor. Test operation at rated current caused matrix overheating, and this was solved by operating at reduced current.

The safety system operated with complete success during the entire 600+ hours of fatigue testing. Faults generated by an operator, the converter, or the drive system all shut down the test article and drive without damage to either. There were no failures of the safety system during the fatigue-test period.

Lessons Learned from DGD1 Testing

The following lessons were learned from the extensive DGD1 testing.

- Automatic control of DC bus voltage proved more difficult than expected, due to the narrow range of voltage regulation required and the gearbox oscillation frequency.
- The generator output voltage versus excitation and speed should be designed to match the converter system. The converter's DC bus should be designed to withstand voltages in excess of the maximum voltage available from the generator.
- The generator output voltage, unloaded over the entire speed range, should be tested before the generator is connected to the converter system.
- For generator voltages in excess of 600 VAC, the generator windings should be form-wound and designed for medium voltage.
- All converter inductors should be designed for convective airflow and be thermally modeled prior to field installation.
- All converter inductors should be constructed without the use of splices.
- The entire converter should be tested at rated temperature prior to field installation. The converter should be modeled thermally prior to and during production testing. The test facility should have sufficient airflow to duplicate the outdoor wind conditions during full-power operation of the converter.
- The gearbox and main shaft natural frequency should be determined as early in the testing process as possible. Drivetrain oscillations occurred at power levels greater than 50% and were damped using high-speed, software-designed notch filters on the generator torque command within the system converter.
- Permanent-magnet generators with form-wound coils should be used on the next-generation drivetrain to eliminate the causes of nearly all of the DGD1 generator failures.
- A safety system should be used to ensure proper control of the test article and drive during fault conditions.
- Proper fusing and circuit breakers should be used to prevent damage to the test article and drive.

- The generator-to-gearbox interface should be tested before final assembly and shipment to the test site, and should be sealed to prevent contamination of the generator's windings.
- The use of DC bus resistive load banks proved successful in generating the extra load needed by the generator-gearbox system—load that the converters were unable to provide. These load banks also helped greatly in keeping the DC bus voltage under control.
- The use of the DC bus to detect generator and rectifier faults through the use of "ripple current" fault monitoring proved successful. This enabled the system to monitor generator-rectifier health through the converter controls without additional current measurement, fuses, or other external items.

The lessons learned from these test results were incorporated into the turbine design process of the 2.5-MW Quantum Drive.

Prototype 2.5-MW DGD4 Quantum Drive: Design, Construction, and Tests

The design of the Quantum Drive (and all other elements of the C93 Liberty prototype turbine) evolved over the duration of the project, and the optimization of the design continued through 2008. The resulting proprietary design documents (more than 4,000 pages) support the configuration of the 2.5-MW DGD4.

DGD Prototype Configuration and Cost Study

In 2002, while construction of the prototype 1.5-MW DGD1 with eight generators was being completed, design-cost trade-off studies were conducted as part of the early design process for the DGD4 four-generator drivetrain. Originally conducted for 1.5-MW to 1.8-MW rating, the design later was scaled up to 2.5 MW. The study compared the eight-generator configuration and several others for application to permanent-magnet generators. The permanent-magnet generators considered worked more efficiently at lower speeds and had a greater power factor. The gear design was optimized by finding the bull-gear diameter, resulting in lowest system cost. In the trade-off study, generator cost was based on an integrated design with salient pole construction. The active material cost (the cost of iron, copper, and magnets in the electrical circuit) was based on an equation from the NREL-funded WindPACT study (Poore and Lettenmaier 2003) which was modified to include end-turn effects.

In August 2003 the prototype configuration was changed to 2.5 MW to enable competition in the projected wind-turbine market. Responding to information gathered from tests of the DGD1 and from the results of the trade studies, the DGD4 Quantum Drive was engineered for testing at NREL on the 2.5-MW dynamometer. Testing the generators earlier identified issues that were corrected prior to testing the DGD4 at NREL. Testing ran from October 2004 through January 2005. The NREL dynamometer testing enabled validation and optimization of key design parameters of the DGD4, and mitigated the risk of installing an untested prototype drivetrain system in the field.

Estimated System Performance for the Quantum Drive

An extensive design effort culminated in the DGD4 Quantum Drive used on the C93 Liberty turbine as actually built. The studies specified performance requirements for each subsystem and described the modeling and assumptions used. These design efforts also supported the submission of documents to attain design certification.

The patented DGD4 Quantum Drive architecture includes a single gearbox that drives four generators; permanent-magnet generators (Figure 4); individual diode rectifiers for each generator, mounted on the generator; and four IGBT voltage source inverters.

Figure 4. One of four permanent-magnet generators for the DGD4 Quantum Drive

Dynamometer Test Plan Overview for the Quantum Drive

Dynamometer testing included the gearbox, generators, converter, and controllers. When the 2.5-MW DGD4 was tested at NREL, the 2.5-MW dynamometer could not deliver the necessary combined power and speed required for evaluating the full operational range of the DGD4 system. The evaluation test therefore was limited to approximately 75% of rated output. Power output also was limited to 1.8 MW, due to the limitations of the 575-to-690-V transformers used as part of the test setup.

The general objectives of testing the DGD4 drivetrain in the NREL dynamometer facility were as follows.

- Evaluate tooth-load distribution on high-speed gear-to-pinion meshes and validate tooth-geometry design optimizations as necessary.
- Evaluate tooth-load distribution on low-speed gear-to-pinion meshes and validate tooth-geometry design optimizations as necessary.
- Evaluate the mechanical torque load share of gearbox output shafts.
- Measure drivetrain component efficiencies.
- Evaluate power converter and generator functionality.

- Develop thermal characteristics of the generator and gearbox oil cooling systems.
- Identify drivetrain system natural frequency; institute and validate dampening algorithms in power converter.
- Evaluate the system and the input current balance of the power converter.

DGD4 Lessons Learned

After the dynamometer tests the DGD4 tested at NREL was shipped back to Clipper. Improvements were made to increase air flow for cooling and to decrease stator losses. Generator testing at another location was completed in early March and showed improvement in overall generator cooling. The four generators then were shipped to Medicine Bow, Wyoming, and installed on the C93 Liberty turbine.

Additional lessons learned in the dynamometer testing that were applied to the Liberty turbine included the following.

- The initial cooling approach required redesign. The new system performed well in tests and was used in the Liberty turbine.
- Generator control unit (GCU) features that performed well during experiments were used during commissioning of the Liberty turbine.
- Some of the seals were improved in response to test results.

Test Results

In response to information from tests, the following changes were made to the turbine design.

Gear-Tooth Load Distribution

- Measurements of tooth load distribution were made using strain gauges located in selected gear roots for each mesh. Data were recorded at 50% and 72% loads.
- Evaluation of the test results showed that the designs of all gear meshes were acceptable and that tooth-loading design margins were not compromised during operation.

Mechanical Torque Share Between High-Speed Shafts

- Measurements of high-speed shaft torques were made using calibrated strain gauges bonded to each shaft. Data were recorded at 50% and 72% loads.
- Evaluation of test results showed that the load balance of the design was acceptable and design margins were not compromised.

Efficiency Measurements

- Efficiency was estimated for 50% and 72% loads for the entire drivetrain and components.
- Results were inaccurate and were not usable to reliably confirm design estimates.

Thermal Performance

- The prototype generators used for dynamometer testing had poor thermal performance, and an improved design was necessary (as was planned prior to these tests). The generators could not be operated continuously at 72% or greater load without winding temperatures exceeding safe limits.

- High-speed bearing and oil-temperature measurements made at partial load had sufficient margin, and acceptable temperatures were expected during full-load turbine operation.
- Rectifier temperature measurements indicated that a design using a fan was necessary for sufficient thermal margin during full-load turbine operation.

Electrical Performance

- Electrical measurements were made under various test conditions.
- Generator DC output voltages and AC current and voltage waveforms all were consistent with design expectations under different load conditions.
- Converter AC current waveforms had low distortion, indicating that the total demand distortion of the turbine output will be well within IEEE 519 limits.

C93 Liberty Turbine Design Studies

The design studies and test data contributed to the turbine that was manufactured for installation and testing at Medicine Bow, Wyoming. The design work continued in response to test results from the prototype machine. This section focuses on the design studies leading up to erection of the C93 Liberty turbine. The details of the lessons learned from testing the prototype machine also are discussed below.

Overall Design Strategy and Documentation

After the early trade studies, the turbine was designed as a 2.5-MW upwind, variable-speed turbine with 93-m (305-ft) rotor diameter, and was named “Liberty.” Engineers and associated consultants performed design analyses that supported the application to GL for certification of the C89, C93, and C96 turbines.

To guide the design of each component and of the wind-turbine system, engineers and consultants performed loads studies based on models and simulations. Test results from the DGD1 and DGD4 measured at the NREL dynamometer, from component suppliers, and from the C93 Liberty turbine testing at Medicine Bow, Wyoming, were compared against these early design studies to complete the design of the Liberty series turbines for commercial applications.

Loads analyses were performed to evaluate trade-offs of loads and power performance (energy capture). The loads analysis effort of the turbine design supported every other aspect of turbine development. Loads analysis was performed using MSC Software’s Adams (Automatic Dynamic Analysis of Mechanical Systems) coupled with Aerodyn (Aerodynamic Module developed by NREL) and interfaced with Adams (a multibody code for dynamic analysis). Loads specifications based on modeling for the C93 went through 16 iterations. Load specifications for the C96 went through 13 iterations, the last of which dealt with cold-weather applications. Field data from the C93 Liberty turbine at Medicine Bow, Wyoming, validated the loads studies.

Aerodynamic performance was calculated in a two-step process. In the first step, the basic performance of the rotor was calculated, independent of any considerations of the turbine system operation. This most frequently is characterized in non-dimensional terms as the variation of power coefficient (C_P) versus tip speed ratio (TSR). To fully characterize the rotor's non-dimensional performance, C_P-TSR curves were calculated for varying values of blade pitch angle.

In the second step, the C_P-TSR curves were converted to turbine power versus wind speed (power curve). This included the operational characteristics of the turbine system (many of which are discussed in the following sections).

Rotor Development

Major design efforts supporting development of the C93 rotor included the blades, pitch control mechanisms and strategy, and the hub and ring gear.

Blade Development and Testing

Prior to the LWST development project, the WindPACT logistics studies showed that the expenses associated with transportation and installation of large items (e.g., blades, tower parts, nacelle) have substantial step increases between the 1.5-MW and 3-MW ratings. Specific constraints to the cost-effective scaling of conventional fiberglass blade designs were identified for rotors that were more than 80 m (262 ft) in diameter. The studies also suggested that taking advantage of innovative rotor technology would be a promising means of increasing energy capture and thus reducing COE.

The goals set for the initial concept of a 1.5-MW wind turbine were to maximize low wind speed site productivity, mitigate loads, and exploit advanced rotor concepts. Another goal was to develop and apply improved technology for both individual blade pitch control and a novel variable-speed approach.

Several airfoil types were considered for possible use on the purpose-designed blade. After reviewing the alternatives, the DU-series was selected as having the best combination of aerodynamic and structural performance, wind tunnel verification, and a proven track record in commercial-blade applications. In February and March 2003, PROPID (prop ID design tool)—an inverse-design code based on blade element momentum theory—was used to explore trade-offs between major design parameters.

The Liberty turbine provided the mechanisms necessary for individual blade pitch control (IBPC). IBPC is guided by the turbine's sophisticated control system, which optimizes generator speeds and simultaneously ensures appropriate torque levels and blade speeds.

The original NREL contract outlined work to develop an extendable rotor blade (ERB) to further improve energy capture under varying wind conditions. Preliminary work was conducted by Clipper, and a patent was issued in November 2003. The ERB later was renamed the retractable blade rotor (RBR). Design work was conducted in Adams (a multipurpose simulation platform available from MSC Software), and showed the RBR to be a promising technology—but with considerable risk. Clipper and NREL agreed that it would be more effective to take such risks after a complete machine had been tested and marketed. In March 2005 work on the ERB/RBR under the NREL contract was placed on hold.

By the 2003 NREL Design Review, the prototype turbine was envisioned as a 2.5-MW upwind system with blades purpose-designed to increase energy capture and improve structural efficiency and simultaneously mitigate loads increases. Additionally, value engineering was to be applied to reduce manufacturing expenses and to reduce installation costs by constraining the blades to dimensions that allowed two blades to be shipped on each truck. This latter requirement eventually was abandoned as the evolving blade designs created blades too heavy for two to be loaded onto a single truck.

By October 2004, the design constraints for the prototype LWST had evolved to near-final form. The responding blade design went through three versions of design, fabrication, and testing during the LWST project, creating the C93 truncated prototype blade, the C96 full-chord prototype blade, and the C96 as-built blade. The C96 as-built blade set represents the C89, C93, and C96 series construction, and is undergoing static and fatigue tests at NREL.

Blade Version 1—C93 Truncated Prototype Blade

The first blade design was intended to reduce weight and dimensions so that two blades could travel on one truck. To travel on U.S. highways, the highest point on a load must be less than 4.5 m (15.5 ft) from the highway, and the gross vehicle weight must be less than 36,287 kg (80,000 lb). A truncated chord design was developed whereby a 16-m (52-ft) section of the trailing-edge chord was removed, starting about 11 m (36 ft) from the blade root. Initial design studies indicated that little loss of performance would result from this modification. Figure 5 shows transport of the truncated blade.

Figure 5. Transport of a C93 truncated prototype blade

A blade-strength analysis of this design was conducted and a C93 truncated blade was fabricated. The blade underwent loads tests on November 17, 2004, followed by frequency tests on November 24. The tests were performed at the manufacturer and witnessed by a GL certification representative. The extreme positive flap load test showed that the blade would survive the extreme design loads. The test deflections matched the finite element model predictions for a 30-year life that had been developed in the blade strength analysis document. Figure 6 shows static testing of the truncated blade. The C93 truncated prototype blade was certified by GL as having passed the static loads test.

Figure 6. C93 truncated prototype blade undergoing static loads test on November 17, 2004

A set of C93 truncated blades was shipped to the test site at Medicine Bow, Wyoming, for installation on the Liberty prototype turbine. The turbine began operation in April 2005. By July 2005, a power performance shortfall was documented. The blade engineers considered how various errors in the performance estimations could have resulted in the performance discrepancies being measured. As a result of prototype tests Clipper decided not to use this blade design, and the certification document was not released.

Blade Version 2—C96 Full-Chord Blades

Due to the prototype testing results, and to better align Clipper's product offering with its project-development assets, it developed a full-chord, IEC Class IIb, C96 turbine configuration and manufactured the C96 full-chord prototype blade. All of the blades (C89, C93, C96) were built with the C96 laminate schedule, which makes them structurally identical except for overall length. As a result, any differences in blade planform should not manifest as different behavior during a full-scale fatigue test.

The C96 full-chord prototype blade underwent static tests at the manufacturer. In July 2005 a problem was discovered. Positive and negative loads tests and natural-frequency tests were performed on a new blade in February 2006. During static tests, the GL analysis of this blade design showed a need for a reinforced shear web near the root of these revised C93 blades. This need soon was confirmed when the blade being fatigue tested at NREL showed material separation halfway through the required one million cycles. Additional blade tests were conducted at NREL late in 2006.

Blade Version 3—C96 As-Built Blades

Taking the test results into account Clipper moved on to the upgraded commercial blade design, incorporating the GL recommendations for strengthening. A positive flap load test and frequency tests were carried out from February 24 to February 27, 2006, and a witness from GL was present to certify the blade.

Following the successful static test, GL certified the designs for the C93 blades (IEC IIa) (30-year life) and C96 blades (IEC IIb) (20-year life) for strength, fatigue, and deflection, including the T-bolt connection to the pitch bearing. To develop data to certify the T-bolt for future use in the C99 turbine, T-bolts will be instrumented during fatigue testing of the C96 as-built blade at NREL. The two blades received certification reports simultaneously (Germanischer Lloyd WindEnergie GmbH 2006a), and the Liberty turbine blade series (C89, C93, and C96) was design certified by GL.

The market for wind turbines in cold climates is expected to present a significant opportunity, therefore Clipper developed cold-weather specifications. The specifications are intended to establish a set of loads appropriate to IEC Class IIb locations for the major structural and drivetrain components, as well as for partial loads safety factors required by IEC.

Pitch Control System Mechanics

Individual-blade pitch control (IBPC) is an integral part of the C93 Liberty turbine. It enhances energy capture in gusty conditions, decreases vibration-induced fatigue stresses, and allows optimum generator speeds over a wide range of wind conditions. Pitch control is accomplished mechanically at the hub by the pitch control unit. The GL-certified electric pitch system uses three independent DC motors, batteries, and servo amplifiers. The batteries and DC motors are integrated into the safety system to ensure that there are three independent methods of stopping the turbine during an emergency. The motors and servo amplifier were chosen to meet the loads, blade-design, and control requirements.

Hub and Ring Gear

The Liberty prototype hub—manufactured from ductile iron—was designed to accommodate three blades for the C89, C93, and C96 family of rotors. Researchers conducted an extensive fatigue analysis of the CAD-designed hub using a finite element model for analysis of varying principal stress direction. The model was based on the American Society of Mechanical Engineers (ASME) 1995 ASME Boiler & Pressure Vessel Code, Section III, Subsection NB-3216.2. The model results indicated that all hub sections had reserve factors that rendered them capable of handling the predicted stresses and extreme loads for 30 years.

An innovation of the hub design includes openings in the casting to allow access to the pitch control system and the blade roots. In standard hub designs, technicians must leave the nacelle and work outside of the hub to access systems for installation, maintenance, and repair. This new hub design reduces maintenance time by eliminating the need to perform routine maintenance or repairs from outside of the nacelle.

Turbine-Control Algorithm Development

Creating the sophisticated variable-speed control system has been crucial to the successful completion of the LWST development project. Possibilities for improving wind-turbine performance through more sophisticated control have been described in the literature for decades. Research results pointed toward achieving optimizations of power output and management of loads by monitoring and controlling all parts of a wind turbine in response to ambient meteorological conditions. The LWST project enabled development of control algorithms to optimize and regulate the power output and loads of the C93 Liberty wind turbine.

Throughout the design effort, simulation tools were developed and used for testing controls. The Adams simulation platform was adapted for wind-turbine simulation and used to calculate turbine structural dynamics and loads. The Clipper simulation (CSIM) was developed specifically for testing controls. It uses steady-state aerodynamic tables to calculate aerodynamic torque and thrust at the rotor hub, and runs on either a standard PC or within the embedded controller CPU itself. In the standard PC implementation, CSIM is used to test and tune control algorithms. In the embedded controller it is used to test the actual control code for bugs, proper operation, etc. The MATLAB commercial software package was used to perform control design and parameter tuning.

The primary goal of the control algorithms is to optimize and regulate the power output of the wind turbine. Power regulation is not controlled directly, but through the regulation of power products—speed and torque. A secondary goal is to minimize peak and fatigue loads.

An algorithm was implemented for the preliminary wind turbine loads calculations in Adams. This proportional-integral-derivative (PID) algorithm was adopted from the approach used in the NREL-funded WindPACT Rotor Study (Malcolm and Hansen 2006) project. Many simulations were conducted to fine-tune the PID algorithm to meet the goals of limiting the maximum RPM in high winds without increasing fatigue loads in the structure.

A typical approach for variable-speed wind turbines is to match the generator torque to the anticipated aerodynamic torque, so that the turbine will operate at a rotational speed that maximizes the aerodynamic efficiency.

Tower damping is achieved by measurement of tower acceleration and feedback into the pitch system control to minimize tower fatigue. The original tower-damping algorithm, like the PID, was based on an algorithm used in the NREL WindPACT Rotor Study project. During prototype testing it was observed that the algorithm had a tendency to excite some high-frequency blade modes, therefore the engineers proposed a revised algorithm.

A pitch demand command generator was devised to smooth the pitch demands issued by the turbine controller. One challenge associated with this aspect of the controls was to ensure that the vendor implemented this algorithm properly in its servo controller. To verify the algorithm implementation, bench tests were conducted with specific command sequences. The measured pitch motion was compared with predictions to verify the algorithm. Field testing on the C93 Liberty prototype further validated this approach by comparing pitch commands to measured pitch motions and by checking to ensure that rate and acceleration were constrained to the proper limits.

Control System Specifications

During the LWST project, Clipper designed, developed, and patented a portfolio of wind turbine control system algorithms. These algorithms included the Variable Speed Distributed Drivetrain Wind Turbine System (U.S. Patent 7,042,110), the Generator with Utility Fault Ride-Through Capability (U.S. Patent 7,233,129), and the Silicon Controlled Rectifier-Transformer (SCR-T). The SCR-T is a means of generator control that supplies variable voltage control needed for smooth start-up, higher efficiency, and slip control.

Many other control-related algorithms and patents are directly attributed to the LWST project research and development. Control algorithms basic to operation of the wind turbine (including speed and torque control, pitch-angle control, and variable-speed operation) all were developed and validated, and are now operational in the Liberty wind turbine fleet. The control strategy for the C93 and C96 turbine configurations was certified by GL on December 16, 2005 (Germanischer Lloyd WindEnergie GmbH 2005).

The overall wind turbine control system has three main components: turbine control unit (TCU), generator control unit (GCU), and pitch control unit (PCU). The control system is backed up by an independent turbine protection and safety system (TPSS). Test results at the NREL dynamometer are related to control system design. The TCU is mounted inside the nacelle. It is the master control system with algorithms for speed regulation through commands to the PCU, torque regulation through commands to the GCU, and overall nacelle control including yaw and sensor input and output. The TCU functions are described in Table 1.

Table 1. TCU Functions

Two-Way Communications	With GCU and PCU
SCADA communications and data storage	For example, energy production, operating hours, data averages.
HMI communications	Laptops, palmtops, local and remote serial communications. Two ports: one up-tower and one down-tower.
Command torque to GCU	Controls loading of the generators. May be bypassed by GCU to take advantage of GCU's 12-times-faster update rate.
Commands to PCU	For blade position and individual pitch rate control. Includes individual pitch capabilities, pitch angle feedback, and fault capabilities to prevent pitch angle misalignment.
Yaw control	Automatic yawing, automatic cable untwisting, and manual yawing.
Gearbox and generator cooling	Includes pressure and temperature sensing and motor controls such as fans and pumps.
Parking brake control and hydraulic system monitoring	
Systems alarm and fault monitoring	Including gearbox pressures and temperature, generator temperature, bearing temperatures, ambient temperatures, wind speed, hub speed, hub rotation direction, generator speed, tower vibration, nacelle vibration, PCU faults and alarms, and GCU faults and alarms.
Fault analysis	Built-in diagnostic capabilities to help with fault analysis.
Processor of watchdog monitor output	For use with the turbine protection monitor. The watchdog monitor outputs in case of a processor failure.

The GCU consists of four inverters located within two enclosures and mounted either inside or outside the tower. The GCU receives the DC power output of each generator and converts to AC for connection to the utility collection system. The GCU functions as a large "torque actuator" through commands received from the TCU fiber-optic communications system. The GCU provides full two-way communication with the TCU; distributes the 690-V three-phase power, including transformer selection of low voltages such as 120 VAC as required; inverts the DC bus voltage to a constant line frequency output matching the 690-V utility grid; and distributes the load among generators to give balanced power output and damping of the drivetrain torque oscillations among the various individual generators online.

The PCU is mounted inside the wind turbine hub and includes the servo motors and drivers for turbine blade pitch under the command of the TCU. Operation of a redundant safety system is ensured by three independent motors controlled by either a servo amplifier or a battery system (one per blade). The PCU provides two-way communication with the TCU including commands for individual blade pitch position, collective pitch rate, feedback of individual blade positions, and alarm and fault information; independent servo control of each blade pitch position based on a common command structure; emergency feather capabilities using batteries connected to the pitch motors via standard DC contactors; and fault and alarm protection for the servo system, the motors, and all position encoders with capability of switching to emergency feather when required.

Safety considerations were incorporated into the design of the turbine protection and safety system (TPSS). The TPSS protects the turbine during control subsystem failures or upon command by a human operator. It is an independent electrical system designed to pitch the blades of the turbine to their 90-degree feathered position and disable the yawing system under manual or automatic operation.

Any loss of communication between the TCU and the GCU, PCU, anemometer, or primary non-independent vibration sensor also results in a fault from the TCU, identical to the watchdog failure. The 24-V safety loop supply will drop out, resulting in the alarm "pitch to feather" or "emergency feather fault."

Electrical Architecture

Designers sought architectures that would promote high drivetrain efficiency and have excellent response to low-voltage events (referred to as low-voltage ride-through (LVRT)). Designs that inherently would lend themselves to the new utility ride-through requirements imposed in Spain and Germany and proposed by the U.S. Federal Energy Regulatory Commission (FERC) were needed. Strategies included moving converter bus regulation (control) from the utility side to the wind-turbine generator side. Boost topologies (voltage-source topologies) were seen to have an inherent advantage over buck topologies (current-source topologies). Full decoupling of generators from the utility would be required.

Dynamometer tests of generators on the DGD1 and DGD4 and tests conducted at the manufacturer identified problems that were addressed before the Liberty turbine was installed at Medicine Bow. Turbine testing also identified areas for improvement. Final tests demonstrated that the turbine rides through system faults and line outages for up to three seconds. Unity power factor also is produced down to a low percentage of rated power. This reduces the need for VAR correction at the substation.

Power-Curve Studies

Power-curve studies were conducted prior to testing of the C93 Liberty turbine at Medicine Bow, Wyoming. In parallel with the aerodynamic design of the Clipper C89, C93, and C99 blades, the CSIM code was used to model the turbine control system. Beginning in about July 2005, CSIM simulations also were used to model the effect of the turbine controller and turbulent wind inflow on the turbine power performance.

At the start of the blade-design process, power-curve analysis was done using PROPID, which had been tuned for good agreement with published power curves for the LM 44.8 and NM 92 blades. Given the blade characteristics from PROPID, a comparative power-curve analysis was performed using Adams. Good agreement with PROPID was achieved using dynamic inflow. However, when using the equilibrium wake model, Adams under predicted power performance relative to PROPID. During this initial design phase, the inboard chord truncation of the Delft airfoil was accounted for by using a correction factor. On the basis of these predictions truncated prototype C93 blades were built and tested.

Following June 2003, engineers selected WT_Perf as the primary code for performing aerodynamic performance analyses. This switch was made because WT_Perf has better documentation and more consistent maintenance than PROPID, and includes the ability to rapidly develop tables of C_P-TSR at varying pitch angle. When development of the C89 (Class I) and C99 (Class III) blades began in early 2004, WT_Perf had become the standard code used for aerodynamic analysis. Results from the 2005 and 2006 power tests of the C93 Liberty turbine at NREL's Medicine Bow, Wyoming, site showed that this simple modeling over-predicted the power curve.

Revised simulations treated the blade truncation and turbulence. Power curves generated by these simulations matched the C93 Liberty test results more closely, and indicated that the full-chord blades planned for production should see the predicted power curve. The C93 turbine using the truncated blades remained in operation at Medicine Bow, allowing testing and tuning of control algorithms and the system in general. Production C96 blades, design-certified by GL, were sent to NREL's National Wind Technology Center in Golden, Colorado, for static and dynamic testing. Power curve measurements conducted at Clipper Windpower's commercial installations suggest that the turbines operating with the as-built C96 blades meet the necessary power curve. Official measurements conforming to IEC 61400-12 Ed. 1.0, 1998, test protocols will be completed in late 2008.

Two-Ton Jib Crane

A two-ton jib crane is mounted in the nacelle (Figure 7). It services the generators, pinion cartridges, yaw motors, pitch motor/gearbox combination, hydraulic and cooling systems, and service brakes. The crane is a key feature in the strategy to reduce O&M costs by eliminating the need to bring in a crane for minor repairs to the gearbox and generators.

Figure 7. The 2-ton jib crane in the C93 Liberty turbine

The prototype C93 Liberty wind turbine was fitted with a jib crane that functioned adequately but had excessive deflection of the jib boom and reaction rollers. Using finite element analysis, Clipper engineers determined that the deflections were due to low stiffness of the support tube and inadequate strength of the reaction rollers. The jib mechanism was redesigned to reduce boom deflection and stress in the reaction rollers.

Nacelle

The nacelle has full clearance for people to stand and walk while working (Figure 8, Figure 9). The hub is accessed through ports and the rear of the nacelle has a roll-up door.

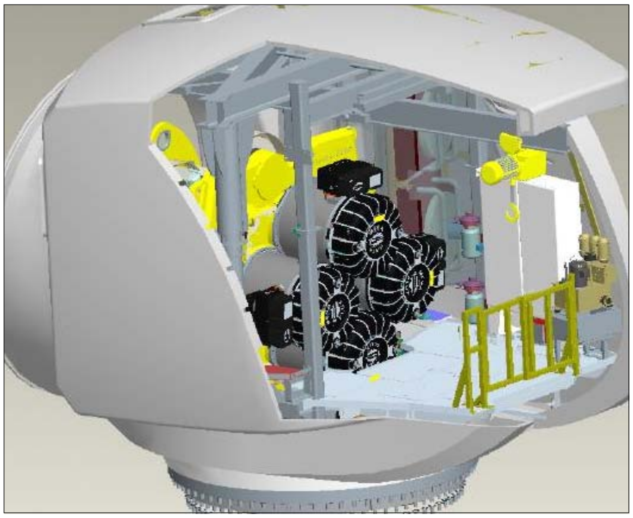

Figure 8. Nacelle assembly

Figure 9. Rear door and cooling vents in the nacelle

Lightning Protection System

The lightning protection system (Figure 10) includes copper blade caps and down-conductors; lightning brushes on the main blade bearings; extensive bonding of all components; a lightning rod located on top of the nacelle; a Faraday cage around the nacelle (EMP shielding); double shielding for all sensor wiring; TVSS protection up and down tower at 690, 480, and 240 VAC; and a low-impedance, single point–style grounding system. The prototype turbine and subsequent commercial turbines have experienced lighting strikes with no interruption in operation and very little damage (Figure 10).

Figure 10. Lighting strike at Steel Winds (Niagara) wind farm in 2007

GL Design Certification

Throughout the design process of the C93 turbine for the LWST project, engineers worked intensively to provide GL with documentation from design studies to achieve certification. Design certification from GL is a necessary step to market acceptance of a new turbine design, especially in Europe.

In response to feedback from GL, Clipper submitted several revised design documents. GL certified each element of the design and eventually certified the entire Liberty turbine system (Germanischer Lloyd WindEnergie GmbH 2006b; Germanischer Lloyd WindEnergie GmbH 2006c; Germanischer Lloyd WindEnergie GmbH 2006d). In 2005 GL certified the design of the C93 turbine, in 2006 GL certified the C96 turbine, and in 2007 GL certified the C96 for cold-weather operation.

C93 Liberty Turbine Testing at Medicine Bow

After extensive design reviews, certification applications, and subcomponent testing, the lessons learned were incorporated into the C93 Liberty 2.5-MW wind turbine for field testing. Field testing began in April 2005 and continued through December 2006.

Field tests were employed to evaluate the integrated system, validate design assumptions, and identify areas for design improvement. Subcomponent evaluations were completed prior to the field test and several design improvements were integrated into the turbine. Some of these improvements were themselves tested during continued prototype operation, others have been incorporated since that time into Clipper's commercial turbine in production.

Lessons learned from building, shipping, and installing the prototype turbine at the NREL test site at Medicine Bow, Wyoming, were documented for use in future turbine installations.

Test Plan Overview for C93 Liberty Turbine

In addition to the overall plan for testing of the C93 Liberty turbine, individual plans to test specific components were developed. The planned test activities are listed below under each component.

Overall Wind Turbine System

Evaluate:

- The power-performance curve to verify power output performance predictions in accordance with IEC 61400-12 Ed. 1.0, 1998;
- Mechanical loads for comparison to the Adams system design model and in accordance with recommended practices in the IEC 161400-13 Draft 8.0;
- The acoustical system performance to determine the apparent sound power level in accordance with the IEC 61400-11 (Ref. 1); and
- The grid compatibility of the system by characterizing the power output quality and conformance to the Institute of Electrical & Electronics Engineers (IEEE) 519 Standard.

Drivetrain System

- Identify drivetrain system natural frequency;
- Institute and validate dampening algorithms in the power converter;
- Evaluate the impact of the rotor installation on the high-speed pinion torque balance and intermediate shaft axial movement;
- Evaluate strain measurements of the forward low-speed bearing race hoop on the main shaft at varying load levels through the operating range of the system;
- Measure lubrication cleanliness levels for quality and for the establishment of future trend analysis; and
- Evaluate the system thermal performance in a rated power, thermal equilibrium state.

Yaw System

- Evaluate the operational performance characteristics for compliance with design specifications;
- Identify and optimize yaw brake friction settings to yield specified performance;
- Measure lubrication cleanliness levels for quality and for the establishment of future trend analysis.

Pitch System

- Evaluate the operational performance characteristics for compliance with design specifications;
- Measure lubrication cleanliness levels for quality and for the establishment of future trend analysis.

Turbine Control Unit

Evaluate the operational performance of the system integrated with the external circuits for conformance with the design specifications.

Power Converter

Evaluate the system thermal performance in a rated-power, thermal-equilibrium state.

Figure 11 shows the C93 Liberty turbine at Medicine Bow, Wyoming, where formal testing and reporting concluded in June 2006.

Figure 11. The C93 Liberty turbine at Medicine Bow, Wyoming

Test Results and Changes Made to the C93 Liberty Turbine

Nearly two years of testing generated the following results and changes to the C93 Liberty turbine. Subsystem improvements also were identified and implemented as the result of field testing. Included were changes to the gearbox, the generator, the power converter, the slip ring, and the acoustic performance of the entire system. An adjustment also was made to the pitch control system to correct for an error in the load estimates. This problem initially was discovered in April-May 2005. Improvements were made that allowed the turbine to run with high pitch-motor and drive temperatures. The entire system was upgraded later in 2005 to fully correct the problems.

Overall Wind Turbine System Test Results

Control System Testing and Data Analysis

Test data collection from the prototype came from three sources: the controller virtual data acquisition system (VDAS), the power-curve monitor, and the loads-measurement system. VDAS can collect any data known to the controller (e.g., RPM, tower acceleration, pitch and torque demands, yaw error) at 20 samples per second. The other sources of data were the power-curve measurement system and the loads-measurement system. The power-curve data included meteorology and turbine power output data at either 1-minute or 10-minute averaging intervals. The loads data consisted of 20 samples per second data from blade and tower bending-strain gauges, shaft RPM, pitch angle, power output, and other loads evidence.

Most of these data were examined with MATLAB or special-purpose data-processing programs. For analysis of the behavior of the control algorithms, RPM and pitch data were viewed both instantaneously and as averages. The instantaneous data helped verify that the time-step-by-time-step behavior of the algorithms was correct. The averaged data provided verification that the trajectories of wind speed, RPM, power output, and other factors matched expectations. Additionally, frequency content analysis also was used to verify certain aspects of the control behavior.

The proportional integral (PI) speed control algorithm was tested in the C93 Liberty turbine. It proved to be robust and effective, however the system experienced frequent over-speed alarms and subsequent shutdowns. Increases in overall gains were tried but success was limited, mostly because the increases that could be applied were restricted to prevent fatigue problems. An alternative gain-scheduling approach was developed that applied large increases in the PI gains only when the rotor RPM exceeded the nominal maximum RPM by a specified amount. This approach was tested and proved successful, so it has been used in the production controls.

Tower oscillations were attenuated using algorithms directing collective blade pitch. Time series data of wind speed, tower acceleration, and tower-damping pitch demand taken in January 2007 at Medicine Bow showed that the high-pass filtering implemented to remove accelerometer drift seemed to be working.

Power Performance

The power performance test program was a cooperative effort of Clipper and NREL. The activities were conducted according to the Power Performance Test Plan. NREL staff provided technical oversight of the instrumentation, data-quality analysis, and development of the Final Test Report. Clipper staff assisted with the instrumentation and with data collection and transfer. These efforts resulted in a Certified Power Curve Performance Report from NREL (National Renewable Energy Laboratory May 2007).

Initially, power performance was below predictions. After eliminating possible causes such as blade-pitch settings, generator features, adjustments for air density, and various control modifications including closed-loop torque control, the shortfall was attributed to under-prediction of the effects of the truncated blade chord. A revised performance prediction was made based on simulation results of the truncated blade profiles with very good correlation to measured performance. Based on the superior performance (energy capture) of the full-chord blade in simulation, Clipper decided to proceed with full-chord blades for the commercial Liberty turbine series.

Power-curve testing was conducted in early 2007 at the Steel Winds project near Buffalo, New York, and was based on nacelle anemometer calibration. (Due to the project's close proximity to Lake Erie, an upwind anemometer placement was not feasible.) IEC-compliant testing for power, loads, and noise currently is underway in Jeffers, Minnesota (Summer 2008).

Loads Testing
The mechanical loads test program was a cooperative effort between Clipper and NREL. NREL staff provided technical oversight of the instrumentation, calibration, and data quality analysis and developed the Final Test Report. Clipper staff installed instrumentation; executed calibration, normal operation, and event-driven tests; and transferred data. These efforts resulted in a Certified Mechanical Loads Report from NREL (National Renewable Energy Laboratory January 2007).

The objective of this test program was to determine relationships between wind conditions and loads on the C93 Liberty turbine under all normal and emergency operating conditions. Comparisons of modeled and observed frequencies at Medicine Bow showed good agreement. A possible exception is observed tower response near 2.6 Hz, which is compatible with the second blade-edge response but not with identified tower response.

The results of this test program were used to confirm computer models of the turbine's response to wind conditions. The test program was designed to conform to the recommended practices of the test specification TS IEC 61400-13.

Acoustic Testing
An acoustic test was conducted on the C-93 Liberty turbine at Medicine Bow, Wyoming, that was a cooperative effort between Clipper and NREL. NREL staff installed the instrumentation and collected data. Testing was conducted according to IEC-compliant techniques. Clipper staff assisted with instrumentation installation and operated the turbine in normal state and as required by event-driven tests. The 2.5-MW Liberty wind turbine is expected to meet contract requirements of 107 +/- 2dB. In addition to the testing with NREL, Clipper continues to study the acoustic characteristics of the Liberty 2.5-MW series turbines and the development of an attenuation package.

Electrics
Grid compatibility was validated. This compatibility had been predicted by previous dynamometer testing and simulations.

Quantum Drive Turbine Test Results
Prior to installation in the C93 Liberty turbine in Medicine Bow, the Clipper DGD1 and DGD4 gearboxes were tested at the NREL dynamometer facility. Although most aspects of the gearbox

design were validated during dynamometer testing, it was not possible to recreate all loading conditions that occur in the wind turbine. The testing at Medicine Bow, conducted mainly from July through October 2006, further validated the following two aspects of the DGD4 drivetrain design, which had incorporated lessons from previous tests: High-speed pinion torque share and intermediate shaft axial position movement. Wind-turbine testing was performed to validate these aspects of the design in the presence of both rotor side loads and normal wind turbine dynamics that did not exist during dynamometer testing.

The C93 Liberty turbine began operation in April 2005 with the totally enclosed water-cooled (TEWC) version of the generators in the DGD4 drivetrain. In August 2006, a new air-cooled version of the generator was installed so that the thermal performance of this system as an integral element of the wind turbine system could be evaluated. The oil, temperature, and load sharing of the gearbox were tested. Torsional resonances were tested on the drivetrain. Two configurations of the generator were tested for temperature rise, as was the power converter.

Tests of Other Components

Gear-Tooth Contacts

An evaluation of tooth contact of the blade-bearing pitch gear was conducted with a total run time of more than 640 hours. Twenty-five percent of the total run time was spent at (or exceeding) rated power output. There was clear evidence that the load was not equally distributed across the gear teeth face, and the wear primarily was concentrated on the hub (inboard) side of the gear teeth. If the gears were produced in accordance with the design tolerances, then this suggests that an opportunity exists to make crowning modifications to enhance the gear life.

Emergency Shunt Regulator

A self-powered prototype emergency shunt regulator was installed and evaluated. The tests identified the emergency feather speed during worst-case regenerative conditions at 240 V. These data were used to validate the thermal design for the emergency shunt transistor.

Yaw Gears

Yaw-gear teeth were evaluated over a total run time of more than 671 hours. Twenty-five percent of that time was spent at (or exceeding) rated power output. The evaluation of yaw-gear load contact included pictures that documented the amount of wear on the yaw-gear teeth. The load appeared to be well distributed, with a detectable bias toward the side opposite the gear drive unit (bottom). There was no indication that uneven or unequally distributed wear was occurring on the yaw-gear teeth around the entire gear ring.

Brake Pads

The brake pads on the four calipers exhibited wear in operation, although the brake was designed only as a parking brake. The cause of the continuous peaks seemed to be a sliding valve (the standard type of port directional control valves) operated with a pulsed direct voltage. Using seat valves instead of sliding valves could eliminate this problem, as the states “open” and “closed” are unambiguously defined.

Jib Crane

The C93 Liberty turbine two-ton jib crane functioned adequately but had excessive deflection of the jib boom and reaction rollers. It was determined via finite element analysis that the deflections were due to low stiffness of the support tube and inadequate strength of the reaction rollers. Redesign of the jib mechanism reduced boom deflection and excessive deflection and stress in the reaction rollers.

Lightning Protection

Lightning protection was tested in October 2005, when lightning struck the blades twice while the machine was running. The machine stayed online and inspection revealed no damage. Lightning receptors at the tip of each blade connect through brushes on the blade bearing and main shaft to carry lightning-strike current down the tower to ground.

Lessons Learned and Applied to Commercial Liberty Series

Testing of the C93 Liberty turbine demonstrated the success of the overall turbine design and enabled engineers to fine-tune the procedures for installing and operating the turbine. Testing also identified areas that required improved components. Some of these improvements required working with suppliers, others involved additional design efforts. The experience of installing and operating the prototype was incorporated into the installation manual of the Liberty wind turbine.

Turbine testing also demonstrated that the safety system functioned as designed. Protocols for continued monitoring of subsystem reliability (e.g., gearbox, bearings, electrical systems) were established. Baseline acoustic measurements were performed so that noise reduction kits could be tested. Baseline system thermal performance was established so that thermal rise control strategies could be tested. Controls tuning (PI on pitch, torque control, and drivetrain damping) took place before any unattended turbine operation. A preliminary power curve was measured and identified issues to be addressed with the blades, pitch angle, and control system. Structural loads testing allowed comparison with tests conducted using the Adams model, and were positive for the projected life of the components.

Gearbox DGD4

The full-prototype testing at Medicine Bow of the C93 Liberty with the DGD4 drivetrain allowed attenuation of resonant frequencies. On the full turbine, the problem became much more complex because there also were frequencies from the blades. As a result of the previous two tests (on DGD1 and DGD4), the strategy had been developed and was simply applied to the more-complex problem. After testing, this strategy also was applied to damp vibration in the tower, to reduce fatigue loads over the turbine lifetime and reduce the amount of materials needed in the tower. This was planned for in the original tower design and verified during turbine testing at Medicine Bow.

Generators

Clipper MegaFlux permanent magnet generator (*see* Patents) is offered on the Liberty commercial turbines. As a result of testing and development under the LWST project, the following features were incorporated: Generator design was improved for greater efficiency and improved cooling; totally enclosing water- to air-cooled generators reduces the risk from contamination. The IP54 air-cooled option (a standard of protection offered by an enclosed junction box that prevents entry of water and dirt) also is available for less-demanding applications.

Testing also demonstrated that the generators could be handled by the onboard two-ton jib crane, and proved that the C93 Liberty turbine can operate with three or two generators if one or two of the four generators cannot function.

Rotor Elements

Prototype testing revealed the shortcomings of the truncated-blade approach and contributed to the new blade design. As a result, a full-chord airfoil was designed.

Yaw System

Yaw brake system hydraulic controls and algorithms were developed and validated during testing of the C93 Liberty turbine.

Nacelle and Two-Ton Jib Crane

The prototype Clipper C93 wind turbine was fitted with a two-ton jib crane. This crane functioned adequately but had excessive deflection of the jib boom and reaction rollers. Engineers redesigned the jib mechanism to reduce boom deflection and excessive deflection and stress in the reaction rollers.

Control System

The Variable Speed System (*see* Patents) was perfected through testing of the C93 Liberty turbine. The generators are completely isolated from grid, which allows for easier voltage ride-through capability and complete isolation from grid disturbance. The control system perfected through full machine testing anticipates resonance conditions within DGD4 Quantum Drive structure and generators, and the software precludes development of harmful vibrations. The turbine exhibited a large power factor when operating on as little as 5% of rated power. The embedded processor for high mathematics-intensive algorithm computation was demonstrated. The perfected control system means the Liberty produces unity power factor down to a very small percentage of rated power—reducing the need for VAR correction. The Clipper distributed static VAR correction system (CVAR) provides VAR compensation and voltage regulation if needed. The turbine meets the current requirement for ride-through with 90% reduction in rated voltage for 150 ms and can exceed this standard by up to three seconds.

Cost-of-Energy Implications

During the proposal process of the LWST development project in 2002, Clipper Windpower calculated cost of energy (COE) according to the detailed instructions in Attachments C and D of the NREL LWST Request for Proposal. Since 2002 much has happened to affect cost estimates. The baseline turbine for estimates in 2002 and 2007 is a 1.5-MW machine. As a result of the LWST project, the proposed 2002 1.8-MW Clipper Quantum turbine configuration was changed in 2007 to the Liberty 2.5-MW, variable-speed turbine—including innovative drivetrain, control system, and nacelle features. These features promise to reduce COE by increasing productivity and reducing operating and maintenance (O&M) costs.

In addition to design validation during the intervening four years, however, materials costs increased significantly. The COE calculations performed in 2006 and 2007 incorporate these higher material costs into both the baseline turbine and the Liberty turbine. Detailed COE data have been presented in the proprietary version of the Low Wind Speed Turbine Development Project submitted to NREL (Clipper Windpower, Inc. May 2008).

To adequately assess the COE implications of the Liberty 2.5-MW wind turbine, COE has been recalculated both for the baseline 1.5-MW turbine and for the Liberty 2.5-MW turbine. The calculations show that the Liberty turbine reduces COE and has increased annual energy production (AEP) compared to the baseline 1.5-MW turbine.

Baseline Turbine and Original Quantum Turbine

The baseline turbine for original COE calculations was a 1.5-MW, 3-bladed upwind design with a 70-m (230-ft) rotor diameter. The drivetrain consisted of a single monolithic wound-rotor generator and gearbox, and partial power conversion system. This machine had variable pitch with individual blade pitch control and was installed on an 80-m (262-ft) tower.

The Quantum turbine evaluated in the original COE calculations was a 1.8-MW turbine with a 60-m to 90-m rotor diameter. Well-controlled variable speed and improved generator efficiency would be accomplished using an advanced, full systems integration approach. The Liberty turbine is a 2.5-MW machine with variable-speed, innovative drivetrain, control system, and nacelle features.

Productivity Improvement

Calculations performed in 2006 were compared with those from 2002 to identify productivity improvements resulting from the LWST development project. In 2002, shaft power curves were forecast for the Quantum 1.8-MW turbine and the baseline 1.5-MW turbine using NREL's WT_Perf performance prediction code and S818, S817, and S816 airfoils. Gross power then was calculated by applying projected gearbox and generator efficiency curves. The turbines were assumed to have 97% availability and 7.8% net losses (between blade-soiling losses, array losses, collection losses through the substation, controls losses, and other miscellaneous losses), for a net efficiency of 89.4%. The distribution of these losses varies slightly from project to project, but 10% to 12% post-drivetrain losses are expected.

Net annual energy production (AEP_{net}) values were calculated as specified by NREL, using sites 1 and 2 described in Table 2 and Table 3. Clipper proposed a third wind site (Site 3) having a high shear ($\alpha = 0.230$).

Projected net annual energy production for the 2007 baseline and Liberty turbines shows between 66.6% and 67.5% improvement in projected annual energy productivity than the baseline turbines (as calculated in 2007). These values are more favorable than those calculated for the baseline and Quantum turbines in 2002 (Table 3). The improvement is attributed mainly to the increase in rotor diameter which increases the rating from 1.8 MW to 2.5 MW. The baseline turbine estimated production is greater in Table 3 (2002) than in Table 2 (2007) because the 2007 models incorporated turbulence, which had the effect of reducing production.

Table 2. The Liberty Turbine Shows Between 66.6% and 67.5% Improvement in Projected Net Annual Energy Productivity over the Baseline Turbine (2007 Calculations)

	Baseline 1.5 MW, 70 m (kWh)	Liberty 2.5 MW, 93 m (kWh)	Productivity Improvement (%)
Site 1 Class 4 – 5.8 m/s at 10 m α = 0.143	4,693,435	7,859,619	67.5
Site 2 Class 6 – 6.7 m/s at 10 m α = 0.143	5,775,437	9,630,251	66.7
Site 3 (proposed) Class 4 – 5.8 m/s at 10 m α = 0.230	6,036,795	10,059,206	66.6

Table 3. Projected Net Annual Energy Productivity for Baseline 1.5-MW and Quantum 1.8-MW Turbines (2002 Calculations); the Baseline Turbine Productivity is Greater in Table 2 than in Table 1 Because the New Models Discounted Production for the Turbulence Expected

	Baseline 1.5 MW 70 m* (kWh)	Quantum 1.8 MW 60–90m (kWh)	Productivity Improvement (%)
Site 1 Class 4 – 5.8 m/s at 10 m α= 0.143	5,155,804	6,692,224	29.8
Site 2 Class 6 – 6.7 m/s at 10 m α = 0.143	6,212,724	7,839,623	26.2
Site 3 (proposed) Class 4 – 5.8 m/s at 10 m α= 0.230	6,462,795	8,242,169	27.5

Operations and Maintenance

Operations and maintenance (O&M) costs were estimated for the baseline and 2.5-MW Liberty turbines in 2007 dollars. This approach to developing O&M expenses puts unscheduled event costs in levelized parts replacement, and focuses on predictable costs including labor, parts, supplies, and administrative support. Scheduled maintenance is assumed to be performed biannually by two full-time maintenance employees. The scheduled maintenance of the Quantum turbine was assumed to be very similar to that of the baseline turbine. The Liberty turbine is expected to deliver O&M cost advantages relative to output, however, due to its innovative design features, including the onboard crane, hub access from inside the nacelle, and four generators.

Levelized Parts Replacement

Estimated levelized parts replacement costs were calculated as specified in the NREL Request for Proposal for the Low Wind Speed Turbine Development Project. The unscheduled replacement costs were calculated by adding the total cost for component replacement, including lost productivity and crane mobilization if required, and then multiplying this by the frequency of occurrences per year. Although these frequencies and times for crane mobilization are somewhat arbitrary and depend on product quality, the resultant costs are thought to be appropriate to cover all unscheduled maintenance, including complete component replacement as well as less important but more frequently occurring issues.

Any failed major component in the baseline turbine caused 45 days of downtime due to the wait time needed for a crane to arrive. Failure of the Distributed Generation Drive main gearing or the rotor also yielded 45 days of downtime. Smaller components could be replaced in one day and were significant only in high-wind periods, which occurred less than 15% of the time. Replacement was completed using the onboard jib crane, and small generators were kept in stock.

Frequency of failure was estimated by experience. The DGD gearing was estimated to fail 33% as often as gearing used in conventional systems, due to its high load tolerance (1:75 turbine-years for conventional gearing, 1:225 turbine-years for DGD gearing). The DGD generators, however, were estimated to fail four times as often as the baseline generators (1:75 turbine-years for conventional generators, 1:18.75 turbine-years for DGD generators).

Cost of Energy

The cost of energy from the baseline turbine and the Quantum turbine was calculated as specified in the RFP. The benefits of including turbines in a 50-MW wind plant are incorporated into the methodology. The initial capital cost (ICC) of the baseline turbine has changed during the period from 2002 to 2007. This change is attributed to an assumed 3% annual increase, due to inflation for items such as labor costs. Material costs also have increased significantly since 2002, therefore the estimated turbine costs have gone up. The analysis shows that, in 2007, the Liberty 2.5-MW turbine produced electricity in a Class-4 wind site at a cost that is 14% less than that of the baseline 1.5-MW turbine. The detailed COE results are presented in the proprietary version of this report (Smith 2001).

C93 Liberty Turbine

Early in the design process, the team decided to move to a larger 2.5-MW turbine to meet a growing market demand for a turbine of this size. New estimates of COE were made based on the new configuration and following the NREL procedures outlined in the Statement of Work. It is thought that the Liberty turbine's COE will be reduced due to design features including the Quantum Drive distributed drivetrain; MegaFlux permanent-magnet generator; variable-speed system; turbine control unit; Clipper VAR control; and ease of assembly, maintenance, and service.

The Liberty turbine is lighter than comparable machines in the 2.5-MW turbine class, therefore it can be installed using cranes sized for commercial 1.5-MW turbines. This reduces the installed cost of machines in the 50-MW wind plant example. The Quantum distributed drivetrain has greater efficiency than that of conventional approaches. The onboard crane and component modularity should reduce O&M costs; however, for these calculations, O&M costs comparable to those for the baseline turbine are assumed. Calculations are based on the 2007 turbine design. Table 4 lists the Clipper wind-class certifications.

Table 4. Clipper Wind-Class Certifications

Wind Class	I	IIa	IIb	III
Rotor (m/ft)	89/292	93/305	96/3,135	99/325
Life	20-yr	30-yr	20-yr	20-yr
Certification	WT-00-012A-2006	WT-00-009A-2006	WT-00-008A-2006	Pending

Conclusions

The COE numbers imply that the Liberty 2.5-MW wind turbine provides a more efficient and cost-effective way to produce electricity than the standard industry baseline turbine. Features of the Liberty 2.5-MW turbine, such as distributed generation drive train, advanced variable-speed system, and advanced controls reduce the cost of producing electricity to less than that of conventional wind-energy technology. These features help to offset cost increases caused by commodity price inflation in the wind-turbine component market.

The COE benefits of Clipper technology could continue to increase in the near future. Improvements in production and manufacturing should come with experience. As these processes become more streamlined and efficient, the COE for the Liberty turbine will continue to improve relative to the COE of standard industry technology. Other factors—such as the expansion of the supply chain and addition of new vendors—also should drive down the Liberty COE.

Commercialization of the Liberty Turbine

The following sequence of events illustrates how the design, testing, and certification activities integrated into the LWST project built the foundation first for Clipper's manufacturing capability and then for project sales and the attraction of key investor BP Alternative Energy.

Clipper Windpower now has offices in California, Colorado, Maryland, Mexico, Denmark, and the United Kingdom, and Clipper is an ISO9001:2000, QMS-certified manufacturer. In 2007, Clipper employed 600 regular full-time employees, in addition to several industry experts who provide consulting services. A Cedar Rapids, Iowa, manufacturing facility—Clipper Turbine Works—will perform final assembly of the gearbox/drivetrain and nacelle. Components designed by Clipper are produced by experienced manufacturers, and U.S. suppliers provide 52% of the components of the Liberty turbine. Progress toward commercializing wind-turbine technology has been greatly accelerated due to the LWST development project (Figure 12).

Commercialization Timeline

First-Generation Technology, Activities in 2001–2004

Clipper developed the first prototype (DGD1) under a cost-shared grant from the California Energy Commission. The prototype was thoroughly tested at the NREL dynamometer in Golden, Colorado, in 2004. Lessons learned from the tests at NREL were applied to the next generation of the multiple-output drivetrain (Quantum Drive DGD4).

Second-Generation Technology

Activities in 2005

The DGD4 multiple-output drivetrain with four generators was tested at the NREL dynamometer test facility.

Activities in 2005–2006

The prototype Liberty turbine was fabricated and shipped to Medicine Bow, Wyoming, where it was erected and commissioned. The turbine was operated and tested in collaboration with NREL over the course of two years, and on March 6, 2005, GL certified the C93 turbine. In September 2005, Clipper completed a successful share placement on London Stock Exchange's AIM and raised more than $130 million; the market cap in 2007 was approximately $1.5 billion. On September 23, 2005, the grand opening of the 9,290-sq-m (100,000-sq-ft) Clipper Turbine Works plant in Cedar Rapids, Iowa, took place.

Activities in 2006

In March 2006, Germanischer Lloyd WindEnergie GmbH (GL) issued a statement of compliance for design assessment of the wind turbine: WT-00-008A-2006 (C96) / WT-00-012A-2006 (C89).

On May 9, 2006, Clipper received U.S. Patent 7,042,110, Variable Speed Wind Turbine Technology. The design incorporated the latest transistors for variable-speed operation and met the IEEE 519 quality power requirements in a faster, simpler manner (*see* Patents).

Commercial Turbines: C93, C96, C99

Activities in 2006

On July 14, 2006, BP Alternative Energy and Clipper Windpower announced their Strategic Turbine Supply and Joint Development Agreement for wind turbine sales contracts. Five wind projects, with an anticipated total generating capacity of 2,015 MW, were planned to be located in New York, Texas, and South Dakota. Also in July 2006, sales agreements were reached with Edison Mission Group, UPC Energy Group, and Florida Power and Light.

The size of the Clipper Turbine Works plant was increased to 19,974 sq m (215,000 sq ft) with a baseline capacity of 350 units per year. The first commercial installations near Niagara Falls, New York, began in late 2006.

Activities in 2007

In 2007, GL issued a statement of compliance for the C93 and C96 models for operation in extreme cold-climate conditions: operating temperatures down to –30°C (–22°F), survival to –40°C (–40°F). Also, the Clipper manufacturing and assembly facility expanded to 30,658 sq m (330,000 sq ft).

In April, Minnesota Power signed a contract for 25 MW (10 turbines). In June, Steel Winds (Niagara) was commissioned as the first C96 commercial project (eight turbines producing 20 MW of power). Preliminary data show that turbines are producing at the expected power curve. The SCADA Web portal indicates production at 4 m/s (9 mph), qualifying these as LWST. The Steel Winds (Niagara) project is in Lackawanna, New York, a Buffalo suburb that has been associated with steel production for more than 100 years. Sited on the bank of Lake Erie, Steel Winds is a redevelopment of a 647-ha (1,600-acre) plot of land long occupied by one of the world's largest steel-production mills. The site's surface is composed of steel slag, a byproduct of the former industrial operations; until now, this hindered redevelopment of the site. Steel Winds uses the old steel mill's roads and offsite transmission lines, which contribute to the efficient and environmental compatibility of the installation. The project won the 2007 Best Renewables Project of the Year Award from *Power Engineering Magazine,* in part because the project demonstrated wind power's potential to revitalize both industrial and rural communities.

In September 2007, Clipper Windpower received an Outstanding Research and Development Partnership Award from the U.S. Department of Energy for the design and development of the Liberty 2.5-MW wind turbine. The Liberty is the largest wind turbine manufactured in the United States.

Also in September, work began on the 60-MW Silver Star project in west central Texas in Eastland and Erath counties. The project includes 24 of the 2.5-MW Liberty C96 turbines and construction is slated for completion in 2008. Ranching activities will continue in this area after construction is complete in 2008. The Silver Star project is owned jointly by Clipper and BP. In late September, BP completed another sales contract for 120 units (300 MW) of Clipper 2.5-MW Liberty Wind Turbines which are scheduled for delivery in 2009.

In October, Clipper announced development of the 7.5-MW Britannia offshore wind turbine. Late in 2007, blades for the C89, C93, and C96 passed the extreme test at the manufacturer, and had undergone extreme loads and fatigue tests at NREL. By the close of 2007, the 68 Liberty turbines commissioned represented 170 MW of generating capacity.

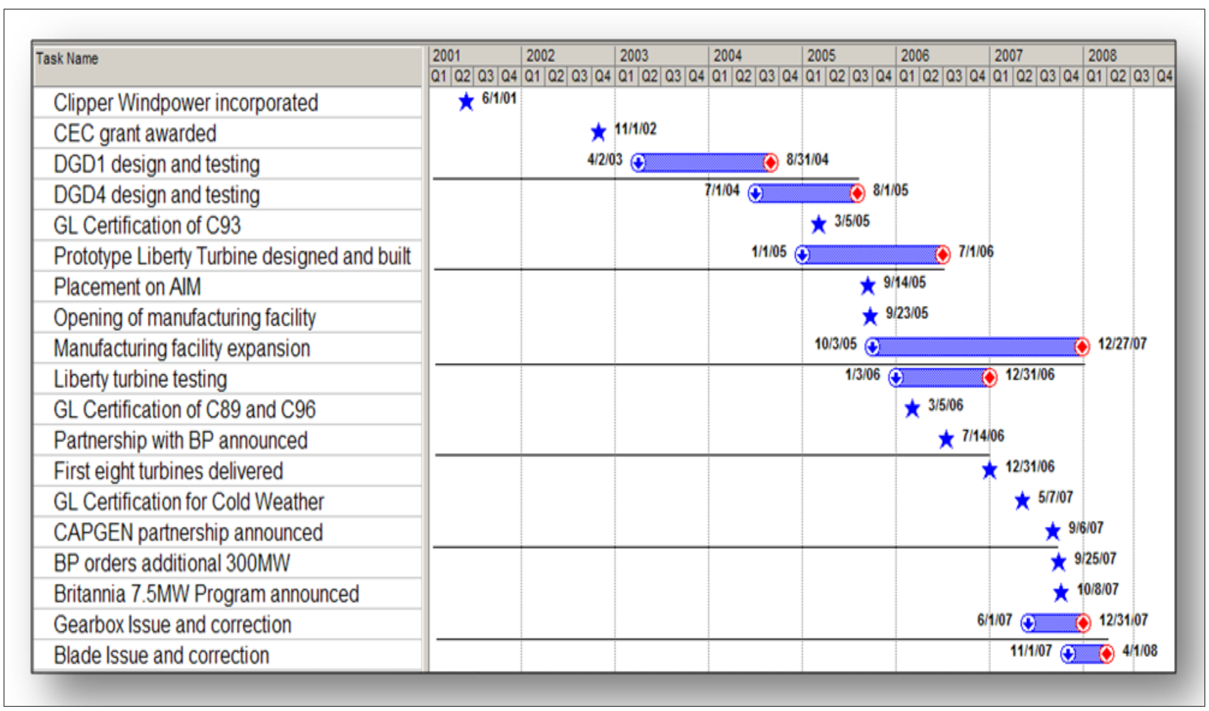

Figure 12. The timeline of Clipper activities and development

Benefits of the Liberty Turbine Development Subcontract

The U.S. Department of Energy and NREL provided financial and technical resources to speed up the application of new technology under the LWST development project. This cost-shared project undertaken with Clipper Windpower moved innovative, distributed-path drivetrain technology and advanced variable-speed controls from design trade-off and bench-scale studies to full turbine testing in record time (2002–2005). As a result of this project, a new domestic supplier is expanding U.S.-based production of MW-scale wind turbines and increasing wind generation capacity in North America.

Financial support, technical review, and test bed activities moved the project forward rapidly. Figure 13 illustrates the cost-share nature of the government investment. Clipper work on the LWST Development Project included:

- Building upon work published by NREL in the WindPACT and Next Generation Turbine studies;
- Applying R&D efforts;
- Incorporating both rigorous design and NREL review;
- Completing test cycles of components and subsystems on various test beds;
- Operating the prototype Liberty 2.5-MW turbine at NREL-managed test site; and
- Obtaining certification from GL.

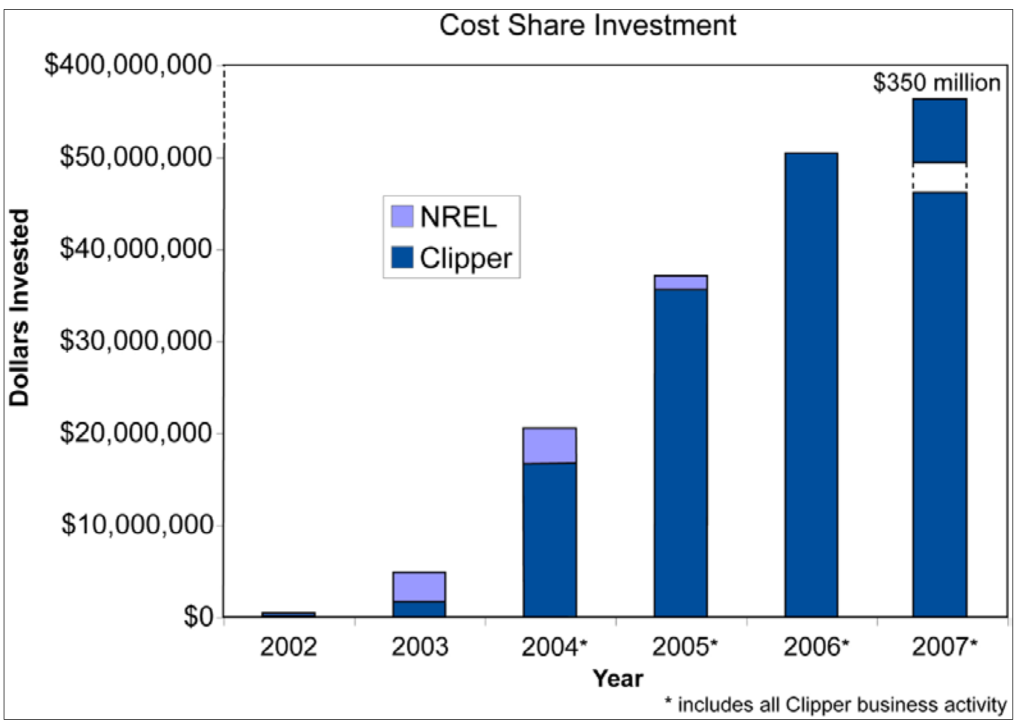

Figure 13. Resources provided by the U.S. government's share of the LWST development project leveraged the investments made by Clipper Windpower to speed development of the turbine design

The LWST project accelerated the entry of a competitive U.S. manufacturer into the market. Figure 14 and Figure 15 show the dramatic impact of the LWST project on the creation of new, quality jobs and the increased amount of factory space at Clipper Windpower as the full-scale production of the Liberty turbine has proceeded. The following facts further illustrate this effect on the commercialization of the Liberty turbine.

- Clipper Windpower factory and associated facilities opened in 2005.
- Clipper turbines are marketed in North America to help alleviate the shortage of turbines.
- Clipper Windpower employs more than 600 people nationwide.
- Sales have grown from 20 MW in 2006 to nearly 800 MW in 2008.

The collaborative strategy of the LWST project has benefited the U.S. taxpayers by creating jobs in the United States and by validating design approaches for low wind speed sites that will reduce costs, improve performance, and ultimately reduce the cost of wind-generated electricity.

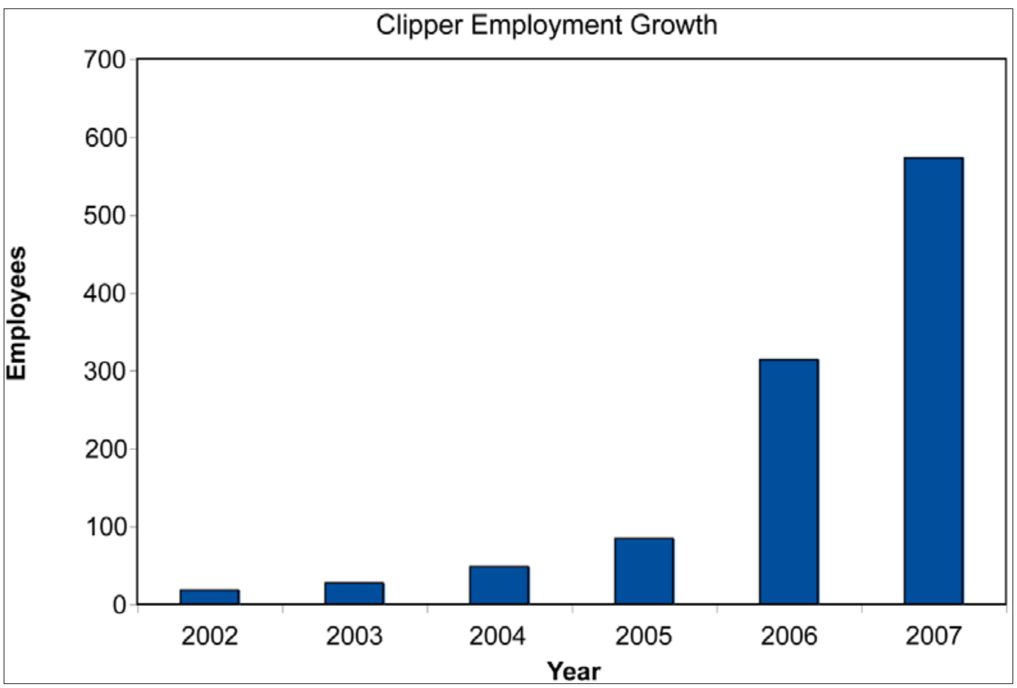

Figure 14. The number of new, quality jobs at Clipper Windpower topped 600 by the close of 2007 as full-scale production of the Liberty turbine ramped up

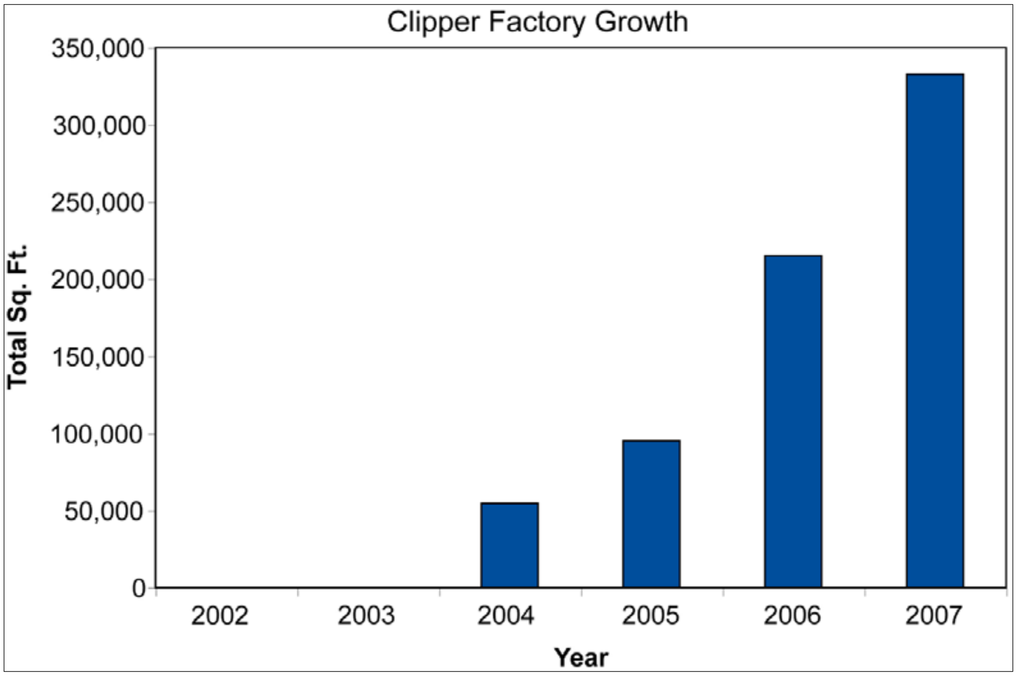

Figure 15. Factory growth matched product orders through 2007

Photo Highlights of Turbine Commercialization

Figure 16 through Figure 19 illustrate aspects of turbine commercialization.

Figure 16. Liberty C96 turbines at Steel Winds (Niagara project), Lackawanna, New York

Figure 17. Staging areas of Clipper Turbine Works plant in Cedar Rapids, Iowa

Figure 18. Dynamometer used for generator tests at Clipper Turbine Works plant in Cedar Rapids, Iowa.

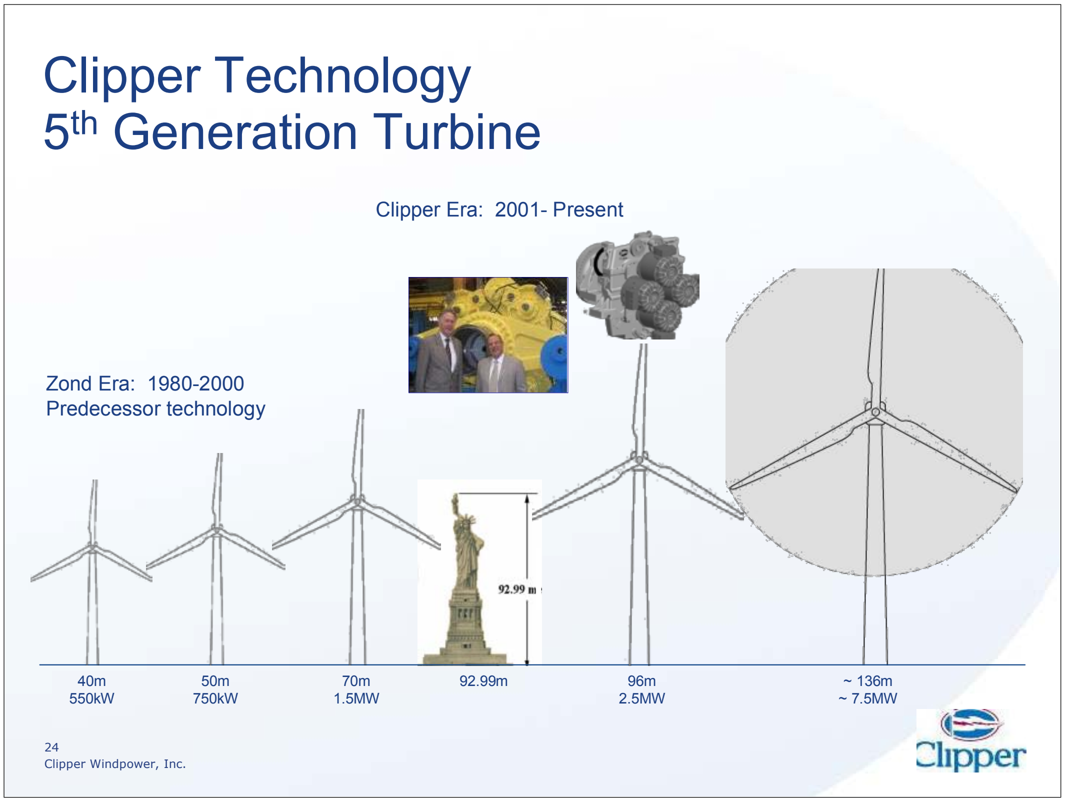

Figure 19. Clipper evolution from the final peer-review presentation of the LWST development project

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Patents

Patents Issued

US6304002 MECHANICAL DRIVE TRAIN: Distributed power train for high torque, low–electric power generator
US6653744 CONTROLS: Distributed generation drivetrain (DGD) controller for application to wind turbine and ocean current turbine generators
US6726439 ROTOR ASSEMBLY: Retractable rotor blades for power generating wind and ocean current turbines and means for operating below set rotor torque limits
US6923622 ROTOR ASSEMBLY: Mechanism for extendable rotor blade
US6731017 MECHANICAL DRIVE TRAIN: Distributed power train that increases electric power generator density
US7002259 CONTROLS: Method of controlling electrical rotating machines connected to a common shaft
US6955025 TOWER: Self-erecting tower and method for raising the tower
US7095597 UTILITY: Distributed static var compensation (DSVC) system for wind and water turbine applications
US6933705 CONTROLS: Generator stator voltage control through DC chopper
US7069802 MECHANICAL DRIVE TRAIN: Distributed power train (DGD) with multiple power paths
US7042110 WTG SYSTEMS / CONCEPTS: Variable speed distributed drive train wind turbine system
US7233129 UTILITY: Generator with utility fault ride-through capability
US7317260 Wind flow estimation and tracking using tower dynamics
US20070187955A1 Multi-generator energy farm with utility fault ride-through capability

Patents Pending (at Close of 2007)

D-1607 Extendable Rotor Blade with Bi-Blade Structure
D-1608 Servo-Controlled Extender Mechanism for Extendable Rotor Blades
D-1715 C-93 Wind Turbine Generator
D-1626 Capacitor Energy Storage for Blade Pitch System
D-1648 Thermal Management System
D-1676 Wind Shear Compensation
D-1679 Wind Turbine Damping of Tower Resonant Motion and Symmetric Blade Motion Using Estimation Methods
D-1684 Multiple-Piece Wind Turbine Blade Fork and Tongue Joint
D-1685 Safety Plug for Sealing Bussbar End Connections
D-1691 Configuration of Wind Turbine Nacelle and Lifting Crane
D-1692 Tension Wheel Hub
D-1709 Retractable Rotor Blade with a Split Trailing Edge
D-1716 Method for Wind Turbine Drivetrain Critical Frequency Exclusion
US20080018309A1 Wind Turbine Generator Apparatus with Utility Fault Ride-Through Capability
US20080007121A1 Power System with Low Voltage Ride-Through Capability

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This report summarizes work conducted by Clipper Windpower under the DOE Low Wind Speed Turbine project. The objective of this project was to produce a prototype wind turbine that can lower the cost of energy in Class-4 wind sites by 2010.

15. SUBJECT TERMS
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