Wind Blade Manufacturing Innovation

Juan Camilo Serrano

Fiber Glass Science and Technology
Outline

• PPG Wind Energy
• Project Motivation and Objectives
• Project Tasks and Results
  – Manufacturing and Automation
  – Materials Evaluation and Testing
  – Predictive Analysis
  – Feasibility Assessment
• Generation Observations and Industry Trends
PPG Wind Energy

- Offering a multitude of products for wind turbines
  - Fiberglass for blades & nacelles
  - Coatings for blades & towers

- World leader in fiber glass manufacturing
  - Established in wind energy for 15+ years
  - Production & Sales from 3 major continents
  - HYBON(R) 2002 and 2001 fiber glass rovings are standard product for wind blades
    - Specified in blades from most major manufacturers around the world.

- Continuing to develop new products to enhance future wind energy production
Project Motivation

- Blades are ~22% of total cost of turbine.
- Existing production process is labor intensive.
- ~60% of the blade is fiber glass.
- Cost of Energy (COE)
  - Today: ~8.2 $ /kWH (on shore)
  - 2030 Goal: <6 $ /kWH

Is there a better way to make blades?
Project Objective

Evaluate the feasibility of automation processes for the cost effective production of wind turbine blades

Technology Approach

- Database review
- Material selection
- Experimental design
- Laminate production and testing
- Process benchmarking
- Manufacturing concept development
- Material processing characteristics
- Surrogate process trials
- Laminate analysis
- Predictive analysis via NUMAD model

Feasibility assessment

Technical

Economic
Project Tasks

1. Materials investigations
   – Database analysis
   – Analysis of performance variables (DOE)

2. Manufacturing and automation
   – Process benchmarking
   – Concept development

3. Process development
   – Material process characteristics and prepreg production
   – Surrogate process trials
   – Laminate production and testing

4. Predictive analysis (FEA)

5. Feasibility assessment
   – Technical feasibility
   – Economic feasibility

Covered by PPG during Sandia Blade workshop 2010
Covered by PPG during Sandia reliability workshop 2011
Manufacturing and Automation:
Process Benchmarking

- Spar Cap Shear Web Design
  - Design Type 2 - Dry Fiber Resin Infused
  - Central Spar Design
  - Box Beam Design

- Spar Cap Shear Web One Shot Infuse Design
  - Type 3 - Dry Fiber One Shot Infusion
  - New "Optimized" Blade Design

PPG Fiber Glass
Expertise you trust. Solutions you demand.
Manufacturing and Automation: Concept Development

- Increase material placement accuracy
- Elimination of wrinkles
- Reduced scrap generation
- Higher throughput in less floor space
Manufacturing and Automation: Machine Capabilities

- Single skin mould lay-up tool or two spar cap lay-up tools
- Capability to produce a blade skin 2.5M minimum root diameter and up to 60M in length
- High speed material processing
- Up to 64 material spools
- Auto-splicing capability
- Fiber placement head
Materials Evaluation and Testing:
Materials Evaluation Matrix

Glass: E-Glass (PPG)
Input: HYBON® 2026
Roving Diameter: 17μm
Linear Density: 2400 TEX

Fiber Production

Infusion

NCF

UD Filament Wound

Reference

Rewinding

Prepreg

Fiber Placement (FP)

Towpreg 1

Towpreg 2

Slit tape

Tape Layup (ATL)

Direct UD Prepreg

NCF prepreg tape
Materials Evaluation and Testing: 
Process Trials with Automated Equipment

Fiber Placement (FP)  
Tape Layup (ATL)
Materials Evaluation and Testing: Static Properties

Potential for 15% increase stiffness with existing materials
Materials Evaluation and Testing: Fatigue Performance

Tension-Tension Fatigue: R=0.1 F=5Hz

S-N Fatigue Curve

At least 1 order of magnitude increase in fatigue performance

Materials Evaluation and Testing:
Fatigue Performance

- UD slit tape
- UD NCF
- UD wide tape
- UD towpreg 1

Technology today
Predictive Analysis:

Objective

- Determine process/property influence on structural performance of a full blade.
- Preprocessing in NUMAD (33 m blade S818)
- Boundary conditions, solving and post processing in ANSYS®
- Input material property data generated experimentally by PPG
  - Effect of fiber properties on blade stiffness, weight

<table>
<thead>
<tr>
<th>Blade Component</th>
<th>Weight (Kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spar Cap (Low Pressure Surface)</td>
<td>1437</td>
<td>30%</td>
</tr>
<tr>
<td>Spar Cap (High Pressure Surface)</td>
<td>1457</td>
<td>31%</td>
</tr>
<tr>
<td>Shear Web (Forward)</td>
<td>53</td>
<td>1%</td>
</tr>
<tr>
<td>Shear Web (Aft)</td>
<td>55</td>
<td>1%</td>
</tr>
<tr>
<td>Skin (Low Pressure Surface)</td>
<td>242</td>
<td>5%</td>
</tr>
<tr>
<td>Skin (High Pressure Surface)</td>
<td>238</td>
<td>5%</td>
</tr>
<tr>
<td>Root</td>
<td>1251</td>
<td>26%</td>
</tr>
<tr>
<td><strong>Total Blade</strong></td>
<td><strong>4733</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Predictive Analysis:

Blade Finite Element Analysis

1. Determine required stiffness from base model
2. Increase blade length
3. Replace material properties with new materials
4. Determine new stiffness and compare to base model

```
NODAL SOLUTION
STEP=1
SUB  =1
TIME=1
USUM   (AVG)
RSYS=0
DMX  = .506204
SMX  = .506204

```

WindPact
Predictive Analysis:
COE Calculation Methodology

Project Assumptions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project size</td>
<td>60 MW</td>
</tr>
<tr>
<td>Wind speed range</td>
<td>13-17mph (Class 4)</td>
</tr>
<tr>
<td>Turbine size</td>
<td>1.5 MW, 33 meter long blade</td>
</tr>
<tr>
<td>Net capacity factor</td>
<td>30%*</td>
</tr>
</tbody>
</table>

COE* = (ICC X FCR)/AEP + AOE

*NREL/TP-500-40566 2006*
Predictive Analysis: COE Findings

- Advanced manufacturing of wind blades with innovative glass fiber composites can enable increased generation capacity and decrease COE
- Asserts the importance of automation as high performance alternative to resin infusion

<table>
<thead>
<tr>
<th>% Increase in blade length</th>
<th>% Increase in weight</th>
<th>% Increase in produced energy output</th>
<th>% Decrease in COE</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.76%</td>
<td>3.5%</td>
<td>7.7%</td>
<td>3.57%</td>
</tr>
</tbody>
</table>
Feasibility Assessment:
Technical Feasibility

• Surrogate process trials:
  – Material quality parameters:
    • Tack, fuzz, width control, flatness, ease of release
  – Material performance parameters:
    • Minimum static and dynamic performance

• Technically feasible approach for production of high fiber volume fraction composites
  – Improved static and dynamic properties (higher stiffness, higher strength)
### Feasibility Assessment:
Sample Material Specification Development

<table>
<thead>
<tr>
<th>Fiber Glass Roving</th>
<th>PPG HYBON 2026</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sizing chemistry</td>
<td>Epoxy compatible roving</td>
</tr>
<tr>
<td>Fiber diameter</td>
<td>17um +/- 3um</td>
</tr>
<tr>
<td>LOI</td>
<td>0.7% +/- 0.2</td>
</tr>
<tr>
<td>Linear Density</td>
<td>2400TEX +/- 200</td>
</tr>
<tr>
<td>Resin system</td>
<td>OOA grade epoxy</td>
</tr>
<tr>
<td>cure temp</td>
<td>80-120 C</td>
</tr>
<tr>
<td>cure time</td>
<td>5H</td>
</tr>
<tr>
<td>Prepreg Resin Content</td>
<td>40% +/- 1%</td>
</tr>
</tbody>
</table>

### Class A
Preimpregnated slit tape

<table>
<thead>
<tr>
<th>Manufacturing Process</th>
<th>Automated Fiber Placement – Slit tape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tack Level</td>
<td>Medium Tack - self adhesion to tooling surface, adequate release from separation media</td>
</tr>
<tr>
<td>Separation media</td>
<td>Siliconized paper, PE or equivalent.</td>
</tr>
<tr>
<td>width</td>
<td>12mm +/- 0.7 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.35mm +/- 0.05 mm</td>
</tr>
</tbody>
</table>

### Class B
Unidirectional Towpreg

<table>
<thead>
<tr>
<th>Manufacturing Process</th>
<th>Automated Fiber Placement – Towpreg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tack Level</td>
<td>Medium Tack - self adhesion to tooling surface, adequate release from separation media</td>
</tr>
<tr>
<td>Separation media</td>
<td>No separation media required if appropriate tack is achieved</td>
</tr>
<tr>
<td>width</td>
<td>12mm +/- 0.5 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.35mm +/- 0.07 mm</td>
</tr>
</tbody>
</table>
Feasibility Assessment:
Sample Material Specification Development (cont'd)

Packaging Requirements (applicable to class A and B materials)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll diameter</td>
<td>76.2mm</td>
</tr>
<tr>
<td>Material build up diameter of core</td>
<td>101.6 mm OD or greater on 76mm core</td>
</tr>
<tr>
<td>Package Length</td>
<td>25.4 cm long centered on core, helically wound</td>
</tr>
</tbody>
</table>

Minimum Performance Requirements

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength - X</td>
<td>1350 MPa</td>
<td>min ISO 527-5</td>
</tr>
<tr>
<td>Tensile Modulus - X</td>
<td>48000 MPa</td>
<td>min ISO 527-5</td>
</tr>
<tr>
<td>Fiber Weight Fraction</td>
<td>76.5%</td>
<td>+/- 1% ISO 1172</td>
</tr>
<tr>
<td>Tensile Strength - Y</td>
<td>50MPa</td>
<td>min ISO 527-4</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>59%</td>
<td>+/- 1% ISO 1172</td>
</tr>
<tr>
<td>Fatigue Performance</td>
<td>(Tension-Tension R=0.1 F- 5 Hz) 2 mm thick laminates (slit tape and Towpreg1)</td>
<td></td>
</tr>
</tbody>
</table>

See slide 16
Feasibility Assessment:
Economic Feasibility

Method 1
- Shell: Vacuum Infusion
- Spar cap: Vacuum Infusion
- Root: Wet layup/Infusion

Method 2
- Shell: Vacuum Infusion
- Spar cap: Automation
- Root: Wet layup/Infusion

Method 3
- Shell: Automation
- Spar cap: Automation
- Root: Automation
Feasibility Assessment:

Procedure

Benchmark: 40 m blade, 3.1 MW turbine for class IV wind

- (BOM) from the FEA model
- Total man-hours per blade (Direct Labor)
- Production time per blade
- Capital equipment
- Depreciation and overhead

Financial Analysis

Total Blade Cost

Predict Income statement

Estimate cash Flows for 10 years
Feasibility Assessment:
BOM – Infusion/Automation

Method 1 BOM Total $53,836

Method 3 BOM Total $69,420
## Feasibility Assessment:
### BOM and Manufacturing Time

<table>
<thead>
<tr>
<th></th>
<th>Fabric Infusion Method 1</th>
<th>Automated Spar Cap Method 2</th>
<th>Fully Automated Production Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOM (USD $)</td>
<td>$53,836</td>
<td>$60,838</td>
<td>$69,421</td>
</tr>
<tr>
<td>Production time per blade (hrs)</td>
<td>29</td>
<td>29</td>
<td>12</td>
</tr>
<tr>
<td>Total man-hours per blade</td>
<td>770</td>
<td>658</td>
<td>331</td>
</tr>
<tr>
<td>Total direct labor cost per blade ($)</td>
<td>$30,800</td>
<td>$26,320</td>
<td>$13,240</td>
</tr>
</tbody>
</table>

### Graphs
- **Fabric Infusion**
  - BOM (USD $)
  - Total man-hours per blade
  - Total direct labor cost per blade ($)
  - Production time per blade (hrs)

- **Automated Spar Cap**
  - BOM (USD $)
  - Total man-hours per blade
  - Total direct labor cost per blade ($)
  - Production time per blade (hrs)

- **Fully Automated Production**
  - BOM (USD $)
  - Total man-hours per blade
  - Total direct labor cost per blade ($)
  - Production time per blade (hrs)
Feasibility Assessment: Man-hour Distribution
## Feasibility Assessment:
### Facility Requirements

<table>
<thead>
<tr>
<th></th>
<th>Fabric Infusion Method 1</th>
<th>Automated Spar Cap Method 2</th>
<th>Fully Automated Production Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell mold cycle time (hrs)</td>
<td>29</td>
<td>29</td>
<td>12</td>
</tr>
<tr>
<td>Operational days/annum</td>
<td>250</td>
<td>250</td>
<td>287</td>
</tr>
<tr>
<td>Operational efficiency</td>
<td>85%</td>
<td>86%</td>
<td>90%</td>
</tr>
<tr>
<td># of shell mold tool sets across total number of production lines</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total number of blades per year</td>
<td>1,055</td>
<td>1,068</td>
<td>1,033</td>
</tr>
<tr>
<td>Facility size (sq. ft.)</td>
<td>310,000</td>
<td>310,000</td>
<td>152,741</td>
</tr>
</tbody>
</table>
Feasibility Assessment: Capital Equipment Costs

Manual Infusion (Method 1)
- Shell mold set which includes LP and HP: $2,400,000
- Spar mold set which includes LP and HP: $900,000
- Web mold: $400,000
- Root mold: $250,000
- Automation equipment for shell: $870,000
- Automation equipment for spar caps: $400,000
- Automation equipment for root: $900,000
- Automation equipment for web: $3,400,000
- Automation equipment for finishing: $4,500,000
- Shell plug: $3,400,000
- Spar plug: $28,630,000

Total: $9,620,000

Automated Sparcap (Method 2)
- Shell mold set which includes LP and HP: $3,200,000
- Spar mold set which includes LP and HP: $1,600,000
- Web mold: $580,000
- Root mold: $870,000
- Automation equipment for shell: $400,000
- Automation equipment for spar caps: $1,600,000
- Automation equipment for root: $600,000
- Automation equipment for web: $3,400,000
- Automation equipment for finishing: $8,000,000
- Shell plug: $4,000,000
- Spar plug: $250,000

Total: $12,220,000

Full Automation (Method 3)
- Shell mold set which includes LP and HP: $3,400,000
- Spar mold set which includes LP and HP: $1,600,000
- Web mold: $250,000
- Root mold: $870,000
- Automation equipment for shell: $400,000
- Automation equipment for spar caps: $1,600,000
- Automation equipment for root: $600,000
- Automation equipment for web: $3,400,000
- Automation equipment for finishing: $8,000,000
- Shell plug: $4,000,000
- Spar plug: $250,000

Total: $28,630,000
# Feasibility Assessment: Total Blade Cost and Profits

<table>
<thead>
<tr>
<th>Building size (sqft)</th>
<th>Infusion Method 1</th>
<th>Automated Spar cap Method 2</th>
<th>Fully Automated Production Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>310,000</td>
<td>300,000</td>
<td>152,741</td>
<td></td>
</tr>
<tr>
<td><strong>Building cost @ 120$/sf</strong></td>
<td><strong>$37,200,000</strong></td>
<td><strong>$36,000,000</strong></td>
<td><strong>$18,328,920</strong></td>
</tr>
<tr>
<td>Overhead cost per year</td>
<td>$3,100,000</td>
<td>$3,000,000</td>
<td>$1,753,467</td>
</tr>
</tbody>
</table>

**Overhead cost per year**
- **Infusion Method 1**: $3,100,000
- **Automated Spar cap Method 2**: $3,000,000
- **Fully Automated Production Method 3**: $1,753,467

**Blade Sale Price**
- **Infusion Method 1**: $91,160
- **Automated Spar Cap Method 2**: $93,625
- **Fully Automated Production Method 3**: $88,657

**Legend**
- **Blue**: BOM
- **Red**: Total direct labor cost
- **Green**: Indirect cost
- **Light purple**: Depreciation

**Notes**
- Building cost @ 120$/sf
  - **Infusion Method 1**: $37,200,000
  - **Automated Spar cap Method 2**: $36,000,000
  - **Fully Automated Production Method 3**: $18,328,920

**Feasibility Assessment**
- **Total Blade Cost and Profits**

PPG Fiber Glass

*Expertise you trust. Solutions you demand.*
### Feasibility Assessment: Projected Income Statement

<table>
<thead>
<tr>
<th>Income Statement</th>
<th>Infusion Method 1</th>
<th>Automated Spar cap Method 2</th>
<th>Fully Automated Production Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical blades per year</td>
<td>1,055</td>
<td>1,068</td>
<td>1,033</td>
</tr>
<tr>
<td>Gross Sales</td>
<td>$116,068,966</td>
<td>$117,434,483</td>
<td>$113,652,000</td>
</tr>
<tr>
<td>Material Costs</td>
<td>$56,806,599</td>
<td>$64,949,780</td>
<td>$71,725,392</td>
</tr>
<tr>
<td>Direct Labor Costs</td>
<td>$32,499,310</td>
<td>$28,098,869</td>
<td>$13,679,568</td>
</tr>
<tr>
<td>Indirect Costs</td>
<td>$3,100,000</td>
<td>$3,000,000</td>
<td>$1,753,467</td>
</tr>
<tr>
<td>Depreciation</td>
<td>$3,784,000</td>
<td>$3,904,000</td>
<td>$4,442,446</td>
</tr>
<tr>
<td>EBIT</td>
<td>$19,879,056</td>
<td>$17,481,834</td>
<td>$22,051,127</td>
</tr>
<tr>
<td>Profit Margin</td>
<td>17%</td>
<td>15%</td>
<td>19%</td>
</tr>
<tr>
<td>Profit Margin (w/o depreciation)</td>
<td>20.4%</td>
<td>18.2%</td>
<td>23.3%</td>
</tr>
<tr>
<td>Taxes</td>
<td>$6,957,670</td>
<td>$6,118,642</td>
<td>$7,717,894</td>
</tr>
<tr>
<td>Net Income</td>
<td>$12,921,386</td>
<td>$11,363,192</td>
<td>$14,333,233</td>
</tr>
</tbody>
</table>
## Feasibility Assessment:
### Financial Analysis

<table>
<thead>
<tr>
<th></th>
<th>Fabric Infusion Method 1</th>
<th>Automated Spar Cap Method 2</th>
<th>Fully Automated Production Method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Financial Ratios and Analysis Metrics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asset turnover (GS/CAPEX)</td>
<td>2.48</td>
<td>2.44</td>
<td>2.42</td>
</tr>
<tr>
<td>Return on Assets</td>
<td>42%</td>
<td>36%</td>
<td>47%</td>
</tr>
<tr>
<td>ROA (w/o depreciation)</td>
<td>51%</td>
<td>44%</td>
<td>56%</td>
</tr>
<tr>
<td>Return on Capital</td>
<td>27.6%</td>
<td>23.6%</td>
<td>30.5%</td>
</tr>
<tr>
<td>NPV @ 12%WACC*</td>
<td>$53,020,024</td>
<td>$43,008,629</td>
<td>$67,627,336</td>
</tr>
</tbody>
</table>

\( t = 10 \text{ years. Cash Flow projections} \)

### Assumptions on model

3% inflation, 35% tax rate, replacement tooling costs added at year 5

*Kahn, 1995. Comparison of financing costs for wind turbine and fossil power plants. Lawrence Berkeley Lab*
Feasibility Assessment:

Generation Observations

- Integration of material and process is key to optimize manufacturing
- Automation technology has potential for increased performance and manufacturing efficiency, technology is deemed feasible
- Mechanical property improvements could enable COE reductions
- Cost model shows potential payoff for wind blade producers who adopt automation through the complete manufacturing process
- Further material cost reductions (mainly through lower cost prepreg) can enable even higher ROI for automation processing
Industry Trends

Ingersoll to build wind blade demonstrator

With help from a $5 million grant, Ingersoll will invest more than $12 million to build an automated wind blade demonstrator based on the company’s composite fiber placement technology.

Winner: GAMESA Innovation & Technology (Spain)
Partner: Grupo M. Torres (Spain)

Gamesa and M. Torres have developed a new blade technology with a revolutionary, 100% automated manufacturing process. The project focused on the following critical aspects: Blade design, structure materials adapted to the automated process, introduction of innovative tip and root solutions that will improve the aerodynamic performance of the blade (higher production capacity of the wind turbine), automatic lamination of dry glass fibre tape (tap developed by Gamesa and M.Torres).
Worldwide Products

Worldwide Brands

- Direct Rovings
- Chopped Fibers
- Mats & Rovings
- Yarn
- Paper Dry Chop
- Long Fiber Thermoplastics (LFT)
- Mil-Tough® Lightweight Protective Panels
- Insulation and Processed Fibers
Acknowledgements

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**MAG:** Joseph Jones, Mike Grimshaw, Jim Watkins, and Milo Vaniglia

**U Maine:** Jacques Nader, Habib Dagher

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Thanks for your attention!

http://www.ppg.com/glass/fiberglass/markets/Pages/windenergy.aspx
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