



Cost / Performance Tradeoffs for Carbon Fiber in Wind Turbine Blades

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Outline

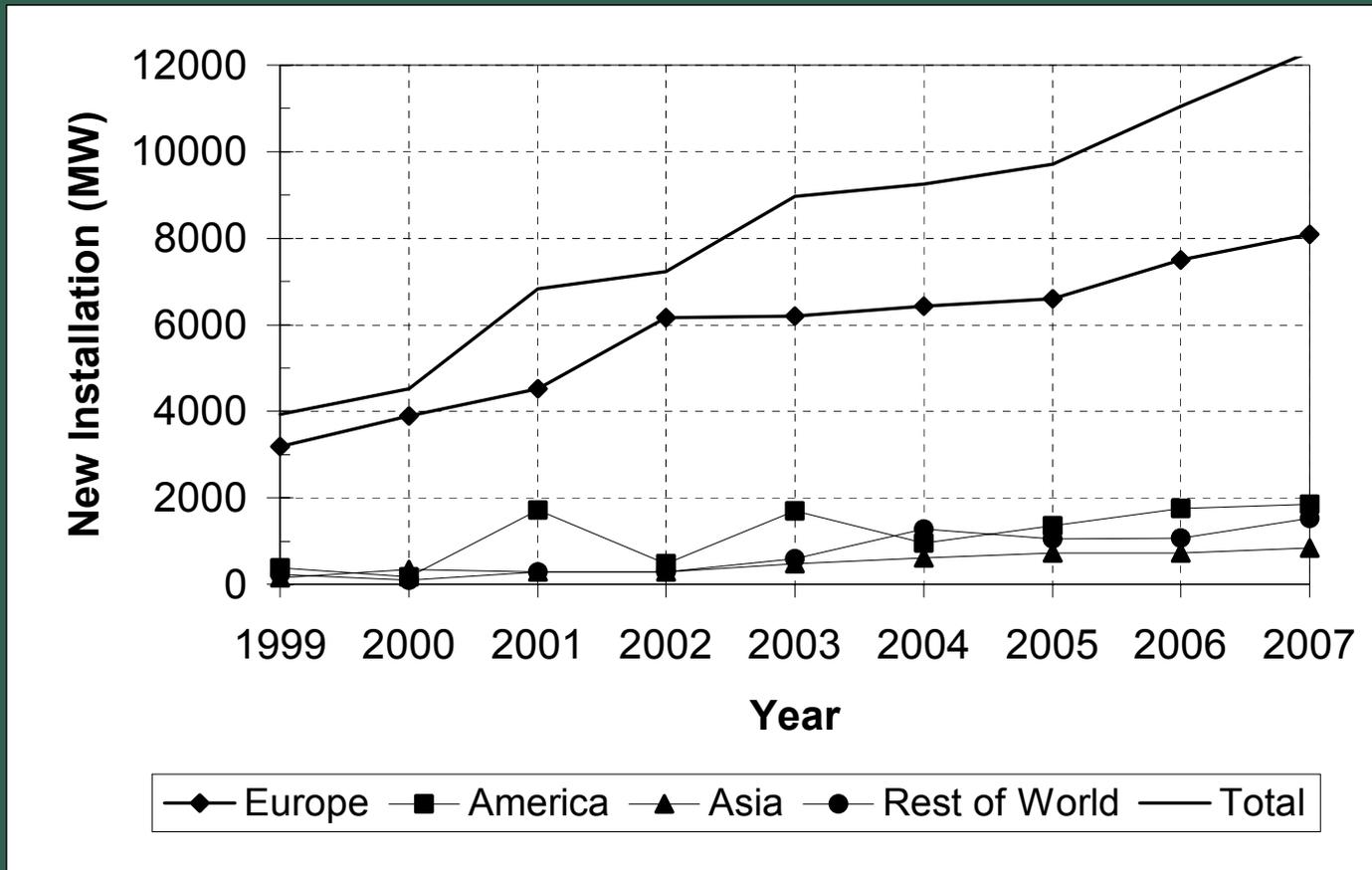
- 1) Wind Energy Market – current size and projected growth – wind energy economics
- 2) Design Drivers and Current Manufacturing Trends for Large Wind Turbine Blades
- 3) Opportunities and Challenges for Increased Carbon Fiber Usage



Wind Energy Market Overview



Wind Turbine Market Overview: Projected Market Growth



Data source: BTM Consult ApS – March 2003, with GEC adjustments for 2003 / 2004



Wind Turbine Market Overview: Estimated Fiberglass Usage in Current Market

- Estimated 2003 worldwide installation of 8,965 MW:
 - Over 110 million kg (120,000 metric ton) finished fiberglass structure
 - \$1.3 billion in blade “sales”
- Market growth averaged 35.7% yearly over past 5 years
- Predicted average annual growth rates of 11% next 5 years, 14% following 5

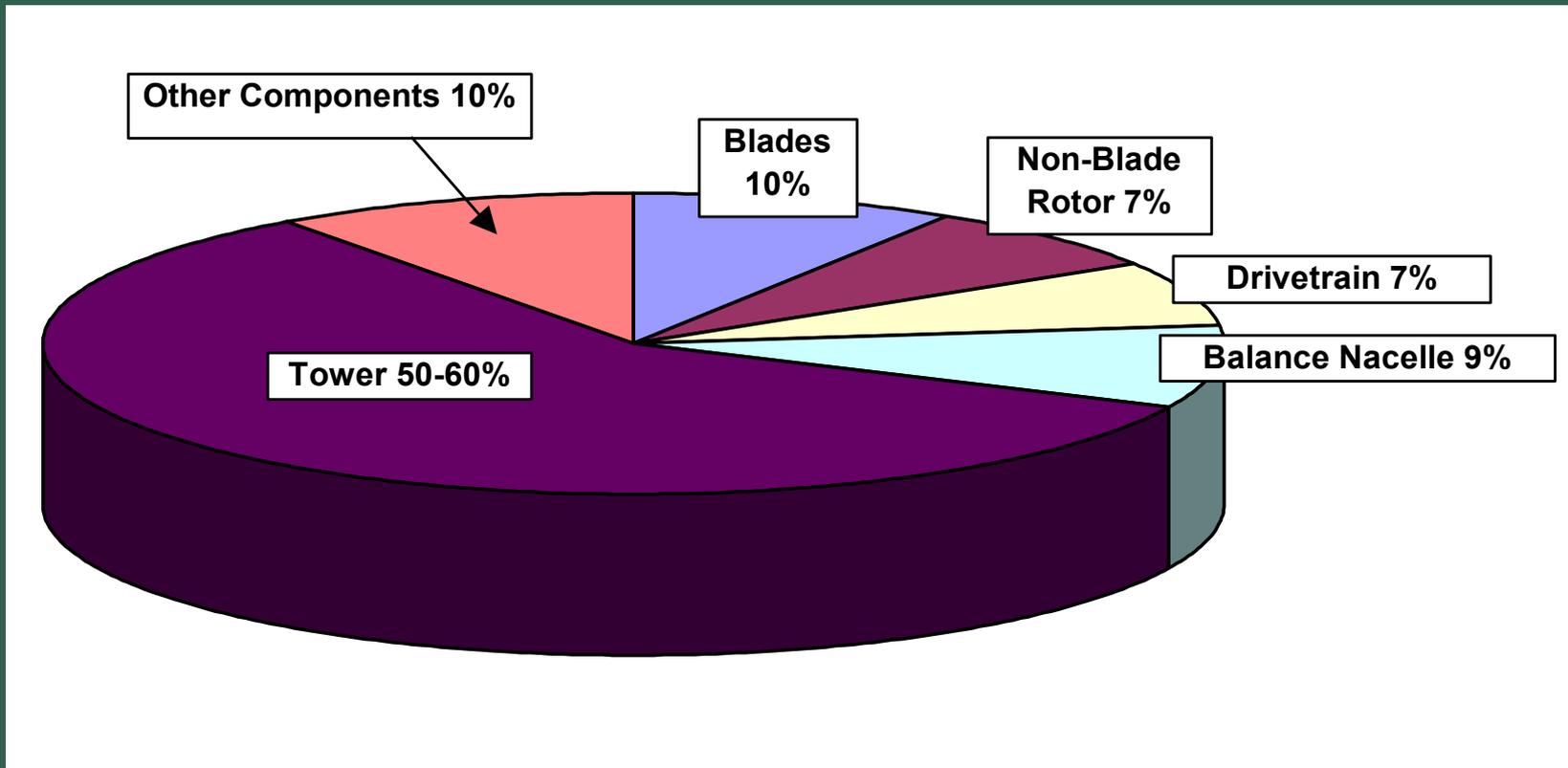


Wind Turbine Market Overview: Potential for Future Carbon Fiber Usage

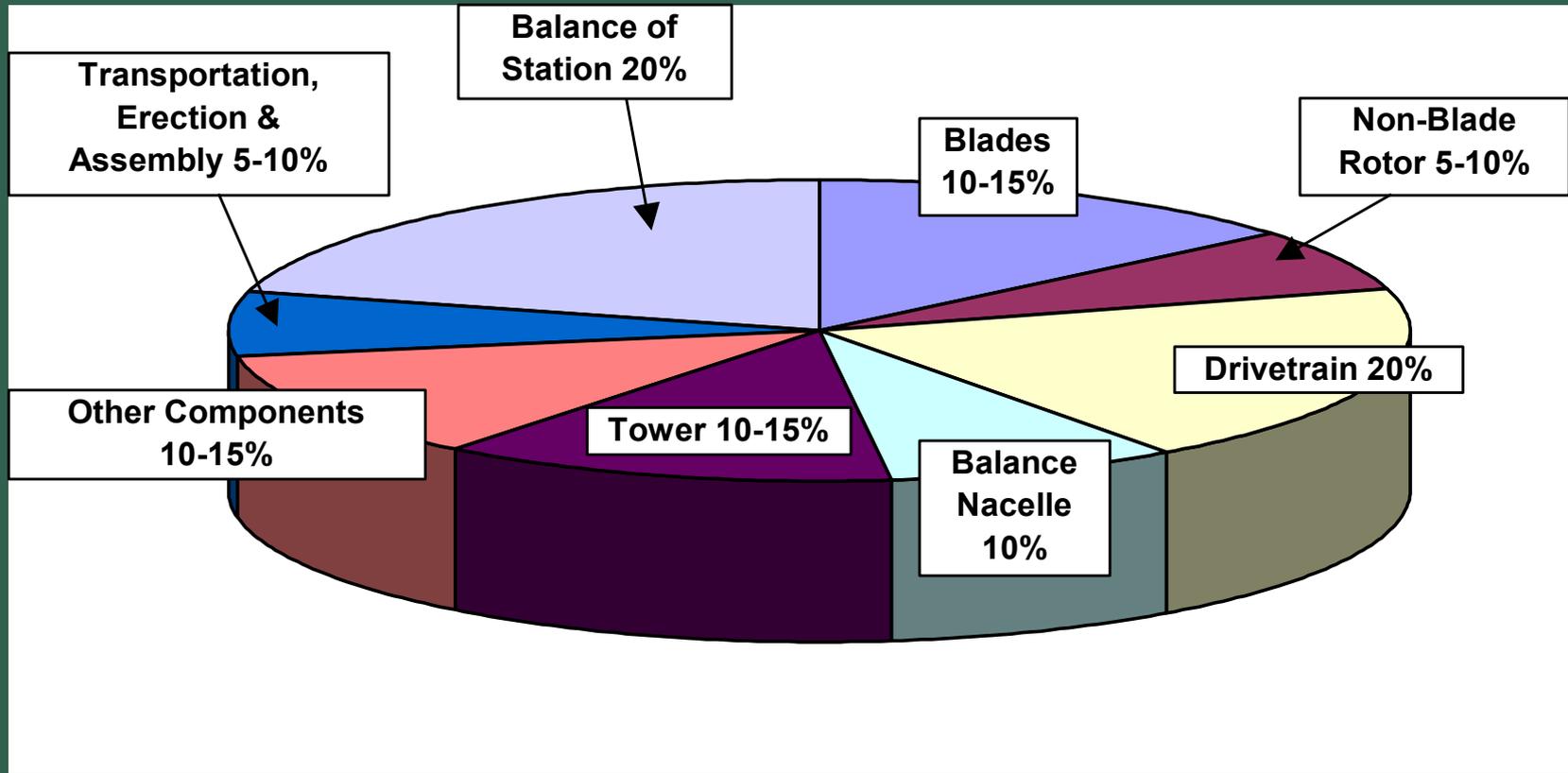
- Initially focused on largest turbine sizes (> 2.5 MW)
- Near-term demand highly dependent on success of Vestas V90 prototypes > extent of and timing of serial production
- Fiber demand in 500 to 1,000 ton range realistic for 2004
- Future depends on decisions by major turbine manufacturers and viability of multi-MW machines:
 - GE Wind, GAMESA, Mitsubishi, REpower, Pfleiderer, Nordex, Enercon, LM
- Trend toward larger machines, offshore, could cause carbon demand could grow faster than overall market



Approximate Breakout of Turbine System Masses



Approximate Breakout of Turbine System Costs





Bottom Line Figure of Merit: Cost of Energy

$$COE = \frac{(FCR \times ICC)}{AEP_{Net}} + AOE$$

Where:

COE = Levelized Cost of Energy (\$/kWh)

ICC = Initial Capital Cost (\$)

AEP_{Net} = Net Annual Energy Production (kWh/yr)

FCR = Fixed Charge Rate (1/yr)

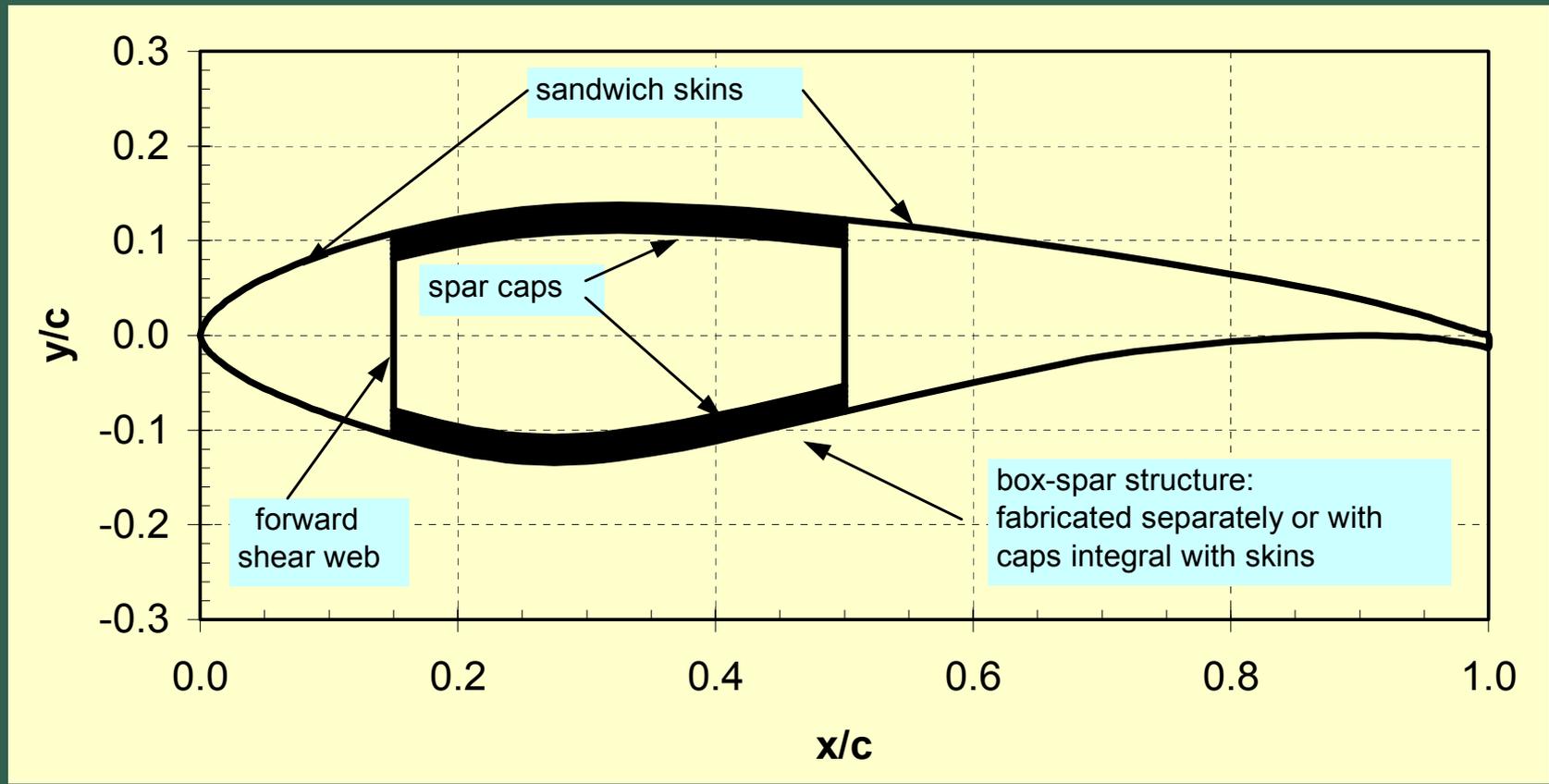
AOE = Annual Operating Expenses (O&M, replacement, land)



Current Design and Manufacturing Trends for Large Wind Turbine Blades



Representative Blade Structure





Trends / Design Drivers for MW-Scale Blades

- Historic use of low-cost materials & manufacturing
 - Open mold, wet lay-up
 - Majority of production now infusion and/or prepreg materials
- Emerging design drivers:
 - Gravity-induced bending loads
 - Stiffness
 - Transportation
 - Continued motivation for load-reducing designs
- Carbon employed in spars for some MW-scale designs



Wide Range of Turbine Sizes – Corresponding “Optimal” Materials & Manufacturing Processes



Photo by permission of Southwest Windpower



Photo by permission of Bergey Windpower Co.



Evolution to Current MW-Scale Designs



V-47 Photograph by GEC, LLC



N80 Photo by permission of Nordex AG



Gravity Loading: mitigated by geometry changes & blade weight reduction



S70 Photo by permission of Nordex AG



V-80 Photograph by GEC, LLC



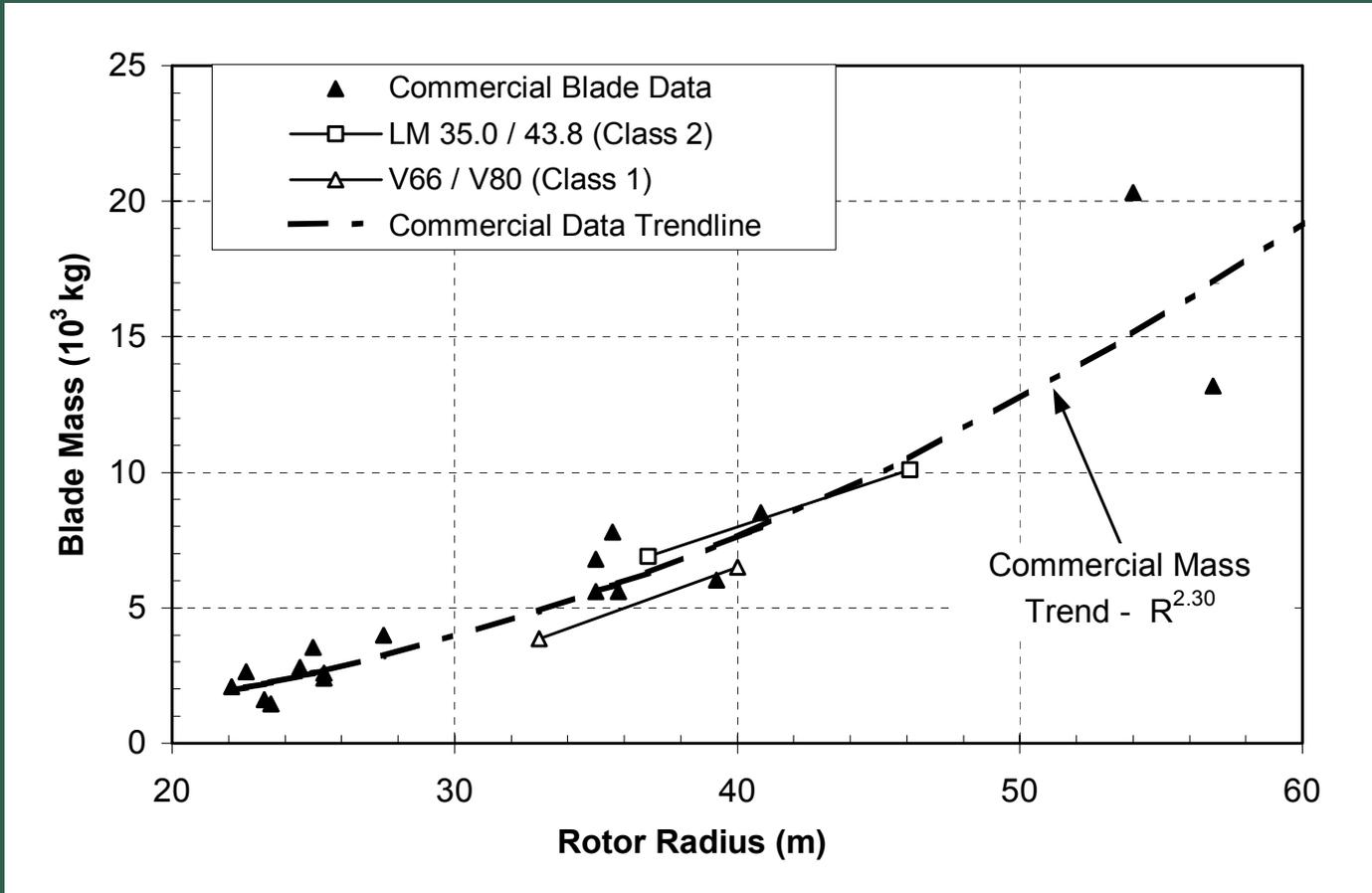
Transportation: length, maximum dimension, & # per load all cost / feasibility drivers



LM 38.8 Photo by permission of LM Glasfiber



Mass Growth Trends for Commercial Blades (primarily fiberglass)





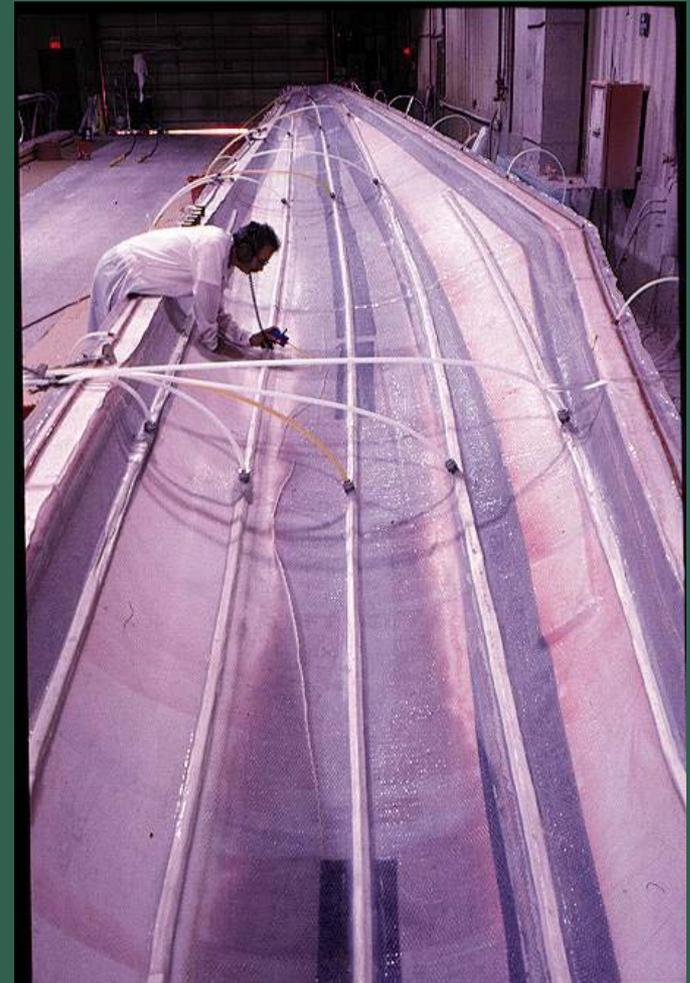
NEG Micon Blade Manufacturing



Manufacturing Photo by permission of NEG Micon



SCRIMP™ Infusion of Blades at TPI Composites, Inc.



Manufacturing Photos by permission of TPI Composites



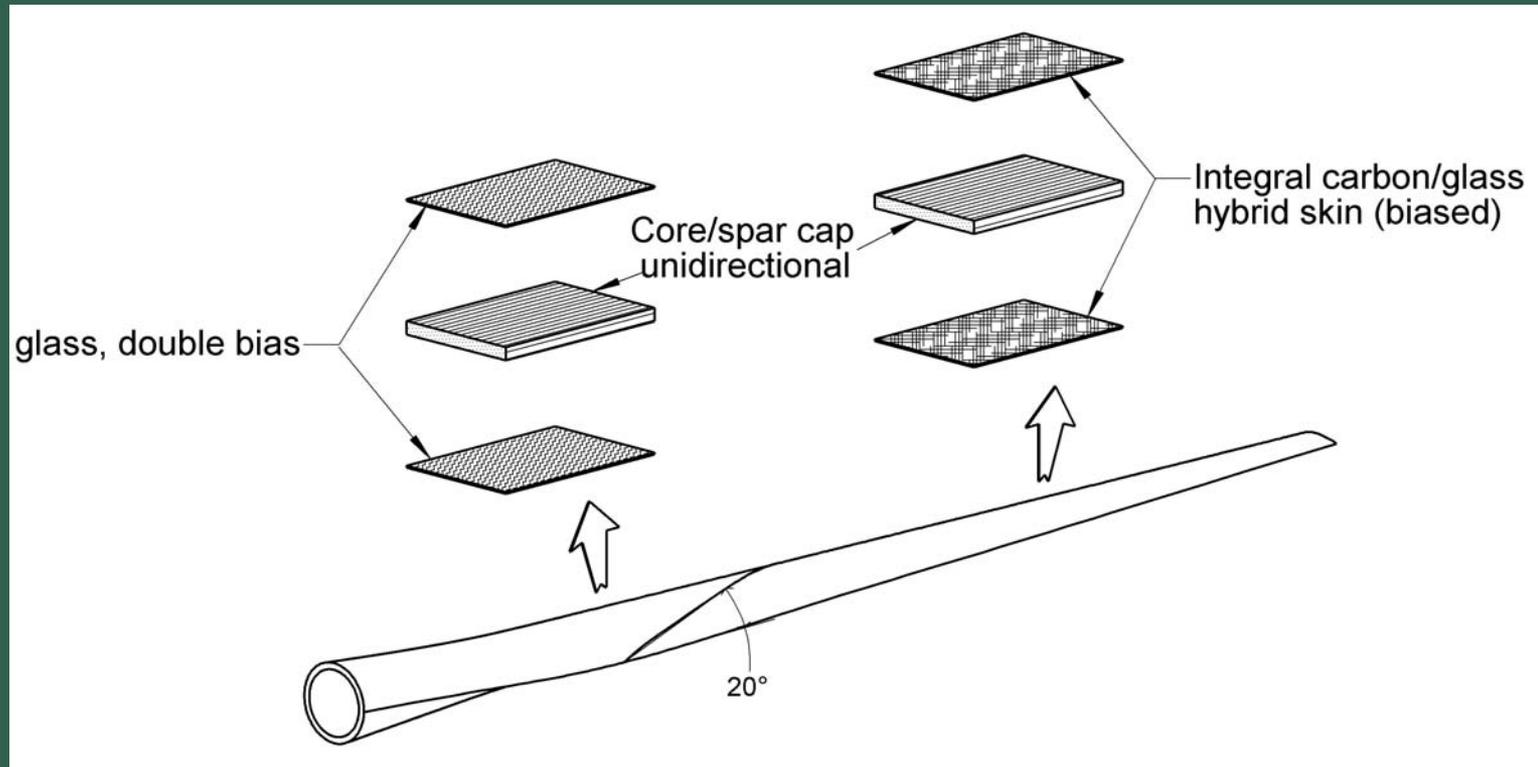
Opportunities and Challenges for Increased Carbon Fiber Usage



“Optimal” Use of Carbon Fiber

- Bulk replacement of load-bearing spar cap
 - European and U.S. studies estimate 32- 38% reductions in mass and 14-16% decrease in blade cost
 - Substantial reductions in tip deflection under load
 - Carbon replacement can be over select spanwise region
- Innovative (load mitigating) blade designs:
 - Slender planforms
 - Aeroelastic tailoring (bend-twist coupling)

Concept for biased carbon-fiberglass blade skins





DOE-Funded R&D for Carbon Fiber Blade Technologies

- DOE/MSU Database Program
- Sandia/GEC WindPACT BSDS:
 - 4 material styles presently in thin-coupon evaluation
 - Prepreg and infused carbon materials
 - Test matrix includes thick specimens, ply drops, ply joints
- Sandia/TPI/GEC/MDZ 9-meter carbon-glass hybrid prototypes
 - Conventional carbon prototypes built early 2004
 - Twist-coupled prototypes built late 2004
- SBIR Phase II
 - GEC/TPI/MDZ
 - K. Wetzel/WSU/GE Wind



Challenges for Increased Carbon Fiber Use

- Baseline cost for fiberglass blades is relatively low
- No apparent fundamental limit to continued fiberglass use
- Cost-of-entry is high for MW-scale blade manufacturing & several years operation before new technologies are “proven” – risk aversion is high
- Majority of large blade manufactures use infusion process, but desirable performance from carbon fiber favors use of prepreg materials
- Cost of energy (COE) reductions limited via blade improvements alone



Opportunities for Increased Carbon Fiber Use

- COE reductions through blade innovations – key is increased energy capture with load mitigation
- Near-term opportunities for carbon highly dependent on success of Vestas V90 turbine
- Benefits from carbon fiber increase for very large machines (e.g. offshore)
- Because of trend toward larger turbines, growth of carbon fiber demand should be substantially larger than overall wind market