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Large Blade Manufacturing Cost Studies Using the Sandia Blade Manufacturing Cost Tool and Sandia 100-meter Blades

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Abstract

This report documents large blade manufacturing cost studies using the Sandia Blade Manufacturing Cost Tool (version 1.0). This blade cost model considers costs for blade materials, labor content, and capital equipment, which are all important factors that are affected by blade design decisions. A key feature of the model is the detailed labor operations breakdown. A conceptual labor process for an example 40-meter blade is defined and used as a baseline labor breakdown for comparisons and for up-scaling the labor content to larger blades. A methodology for scaling the labor content is applied based on geometric scaling associated with individual labor operations. The scaling trends are also investigated for the materials and equipment portion of the costs. One motivation of this work is to perform manufacturing cost studies and assess manufacturing trends and manufacturing needs for large blades, in particular, for the Sandia 100-meter blades (SNL100-XX series). The tool is demonstrated for the SNL100-00 all-glass baseline blade and the SNL100-01 carbon blade. Example sensitivity studies are performed to demonstrate potential use of the tool for cost tradeoffs studies between materials, labor content, and equipment components of cost for blade manufacturing.

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INTRODUCTION

As wind turbine blades grow longer and into the 100m+ ultra-large regime, it is important to understand the changes in design architecture that accompany these large increases in size, but it is equally important to understand the effects of those changes on the manufacturing process and costs. An ultra-large blade may have a feasible design, however if the manufacturing costs aren't feasible then the blade design is unfeasible. Past research has attempted to project the future costs of larger and larger blades, but those projections can be inaccurate and have a low level of detail which does not truly reflect the cost changes. Simple overall scaling laws may not be detailed enough to be of interest to a manufacturer who is concerned about the individual influences of specific cost components and the effects of blade design innovations on blade manufacturing operations and costs. Individual cost components may not scale at similar rates, which limits the usefulness of the purely overall projection-based methods.

This research attempts to bridge design and manufacturing for future blade design concepts. Current proposals for new concepts have no grounding in manufacturing cost-effectiveness. These designs may have excellent performance characteristics by implementing top of the line materials, but those materials may be cost prohibitive in the overall economic analysis of the blade cost. The model described in this report includes a highly detailed analysis of manufacturing costs. These costs are derived from dimensional and material characteristics of the blade design. This model allows proposed blade designs to be compared on level ground so that the cost impacts of design changes can be understood. This allows for better trade-off studies in the design process. Blade design concepts produced using this model will be able to incorporate performance optimization and manufacturing cost optimization into the design process. This model is necessary for the comprehensive analysis of a blade design. The coupling of design and manufacturing will provide a greater understanding of blade concept proposals, which will be more valuable to the manufacturing industry.

This report documents large blade manufacturing cost studies using the Sandia Blade Manufacturing Cost Tool (version 1.0). This blade cost model considers costs for blade materials, labor content, and capital equipment, which are all important factors that are affected by blade design decisions. *A key feature of the model is the detailed labor operations breakdown. A conceptual labor process for an example 40-meter blade is defined and used as a baseline labor breakdown for comparisons and for up-scaling the labor content to larger blades. A methodology for scaling the labor content is applied based on geometric scaling associated with individual labor operations.* The scaling trends are also investigated for the materials and equipment portion of the costs. Again, one motivation of this work is to perform manufacturing cost studies and assess manufacturing trends and manufacturing needs for large blades, in particular, for the Sandia 100-meter blades (SNL100-XX series). The tool is demonstrated for the SNL100-00 all-glass baseline blade and the SNL100-01 carbon blade. Example sensitivity studies are performed to demonstrate potential use of the tool for cost tradeoffs studies between materials, labor content, and equipment components of cost for blade manufacturing.

Additionally, this model provides a method of estimating the effects of manufacturing process changes on the overall cost. If an automation method for a specific manufacturing operation is desired, the downstream effects of additional capital equipment on blade cost can be considered. Further, the effects of material prices, wage rates, and other capital equipment costs can also be considered. The final component of this analysis is a rudimentary calculation of the potential levelized cost of energy for different blade designs. This model produces a $/kWhr value for each blade concept. It shows the possible effects of blade weight reduction on the total turbine system cost. This creates useful scenarios that can compare the overall effects of design performance against blade cost.

RELATED AND SUPPORTING RESEARCH

Previous research into the area of manufacturing cost projections for future blade designs has resulted in a range of estimates for future costs and cost trends. NREL's "2010 Cost of Wind Energy Review" Appendix C provides a scaling equation to determine the manufacturing cost trends of larger blades (up to about 70 meters) and other components (Reference 1). It provides detail of breaking it down into the major components of materials and labor. The resulting total values seem reasonable for future blade designs, but the material and labor components do not match with expectations. This method like many others is primarily useful for determining the scaling relationship of increasing blade lengths for the range of blade lengths in which the analysis was performed, but not for specific, individual changes to a design or the manufacturing process.

The 2001 NREL "WindPACT Turbine Design Scaling Studies Technical Area 1 Composite Blades for 80- to 120-Meter Rotor" report provided methods for calculation of capital equipment costs and results of blade design and cost studies for blades up to about 60 meters (Reference 2). The analysis includes blade design specification (laminate sizing) based on partial safety factors from international design standards and evaluation of aerodynamic design considerations as they affected the blade design specifications such as chord and twist schedule. An analysis of blade costs due to materials and molds/tooling is provided, including an analysis of the effect of various production level effects on costs. However, the manufacturing process operations and associated labor content is not addressed in this report.

The 2003 "Cost Study for Large Wind Turbine Blades: WindPACT Blade System Design Studies" gives much greater detail of the manufacturing process with a breakdown at the major operations level and the material content is specified to specific materials (Reference 3). The WindPACT cost study provided a comprehensive assessment of blade costs including (1) "direct manufacturing costs" such as materials and labor, (2) "indirect manufacturing costs" such as overhead, development, and facilities cost, and (3) transportation costs. Conceptual blade design definitions for blades of lengths 30, 50, and 70 meters were developed based on scaling and simplified structural analysis and then used to estimate the above individual cost components and their trends with blade length. The study assumed that the fundamental design concept and choices for materials within the design were the same for each blade length that was examined. In this sense, this study provided a valuable baseline for both blade cost and trends of costs components (i.e. scaling exponents) for conventional blade designs of length 30 to 70 meters so as to have a reference to compare cost (and weight) of future innovative blade designs. However, due to the limited manufacturing experience of the time, the projections of this model do not seem to hold up when compared to blades of today. This is primarily due to the vast increases seen in the material cost component compared to the others. However, the capital equipment analysis of the WindPACT study seems to meet with current industry expectations, so that exact methodology was used to create the projections for this current report.

A few comments should be made about the current blade cost analysis presented in this report. *The methodology of the current analysis is similar to the approach of the WindPACT study of Reference 3 in that both include the manufacturing process (labor content) costs. However, the current work provides greater detail into labor operations costs at the subtask level and cost trends for labor operations with blade length.* Based the assumptions of this current labor analysis labor cost scaling was found to be lower than the Reference 3 -- further work to examine the detailed labor breakdown is required to understand the labor scaling of different manufacturing processes for blades of today and future large blades. *In addition, the materials costs within the current approach are based on actual and detailed blade design specifications based on recent large blade design efforts at Sandia while other studies consider trends values for materials costs compiled across the industry.*

A user manual is provided for the current tool in Reference 4.

METHODOLOGY AND CASE STUDIES

40m wind blade manufacturing cost analysis

In this work, a conceptual, detailed labor process for an example 40m blade was derived from information from an industry source. A typical two-part clamshell blade using VARTM infusion was used as the baseline for current on-shore blade production. This type of construction uses several preformed components in addition to the blade molds. Preforms are used for components that have high thicknesses and many plies. Preforms are built in parallel with the main blade and added into the main blade lay-up as required. Preforms require separate molds and laborers.

All-glass

The design features a shell with a single web I-beam type spar. The 40m fiberglass blade has preforms for the HP (high pressure) and LP (low pressure) spar caps, shear webs, and root preform. The shell features a thin bias-ply fiberglass skin sandwiching a foam core. The root is solid unidirectional and bias-ply fiberglass. The shear web is a thin bias-ply fiberglass skin over foam sandwich. The defining feature is the solid unidirectional fiberglass spar caps.

Materials

The material content for this 40m blade was estimated based on previous research, the material percentages of the 100m blade, and industrial feedback. The cost of materials was taken from industry feedback. All material prices except the core were based on mass in units of $/kg.

Core

The cost of core for this model is based on the area due to the expense of kitting while also based on thickness. Using a price point of $\$32/m^2$ for 25.4mm thick foam core obtained from an industry source, an estimate of kitting cost was created. The price of kitting was estimated to be a standard of $\$20/m^2$ for any thickness and the thickness cost was estimated to be $0.50/mm. The average thickness of foam in the blade was assumed to be 25.4mm. This gives a total cost of $\$32.70/m^2$, which is close to the total cost provided by industry. To determine the area of the foam in the blade, the areas of the spar caps, root, and trailing edge reinforcement were subtracted from the total surface area of the blade and the area of the shear web was added. The area of the spar caps was simply calculated from their length and width, the root area was from its diameter and mold length (however, the foam may overlap the root preform a small distance), and the trailing edge was from its length and width. The areas for the shear web and shell were calculated from blade models.

A breakdown of material costs by material type for this 40m blade is provided in Figure 1.

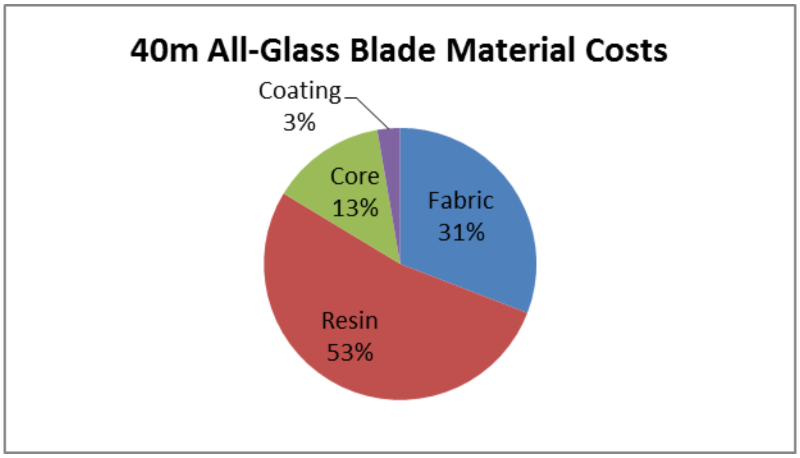

Figure 1. 40m All-glass Blade Materials Cost Breakdown by Material Type

Labor
Labor content was derived from detailed conceptual operations descriptions described above. Only labor hours were considered in the totals reported. A placeholder was included for a trailing edge preform to create identical pie charts for future larger blade comparisons, which may include a trailing edge preform. There are labor hours for trailing edge reinforcements in the 40m blade, but those are wet-lay-ups that are included in the pre-bonding process. The labor content by subtask for the 40m blade is provided in Figure 2.

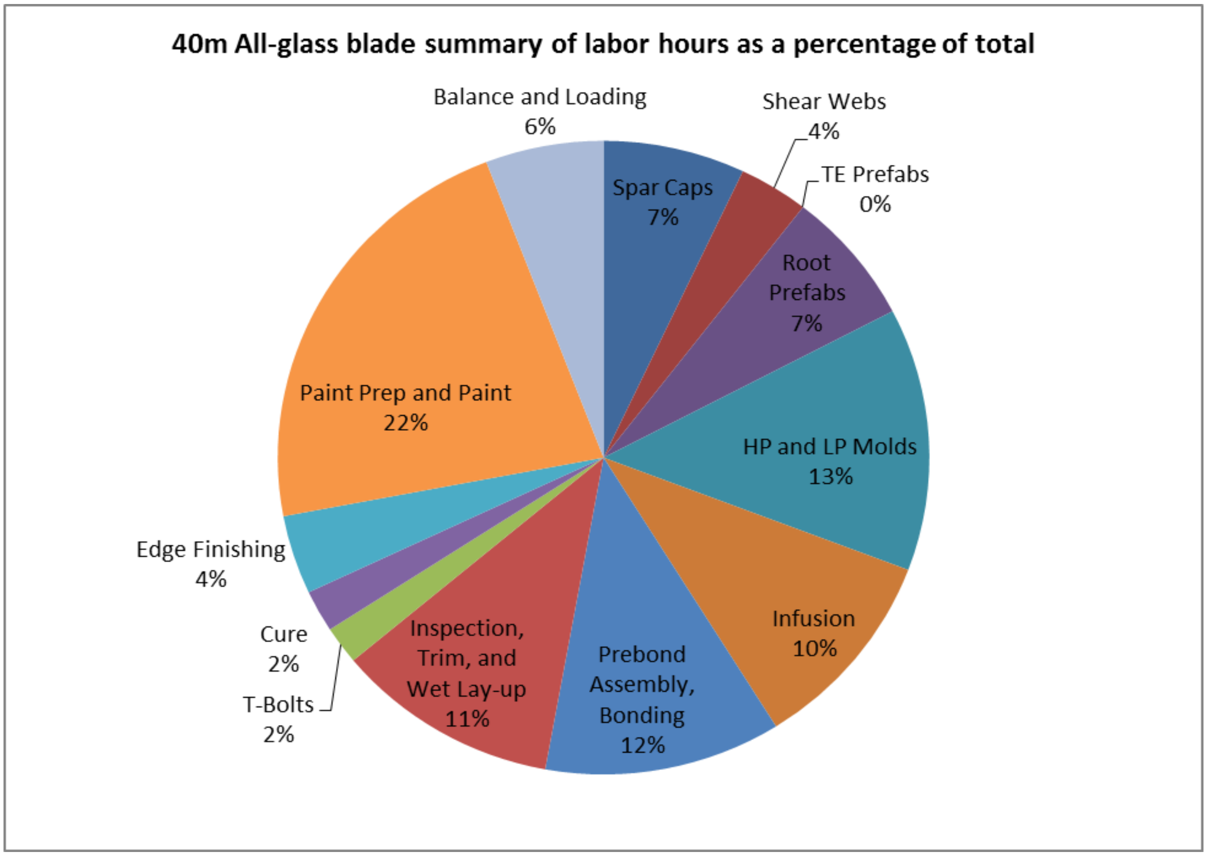

Figure 2. 40m All-glass Blade Labor Content (by Subtasks)

The labor content by major operations for the 40m blade is provided in Figure 3.

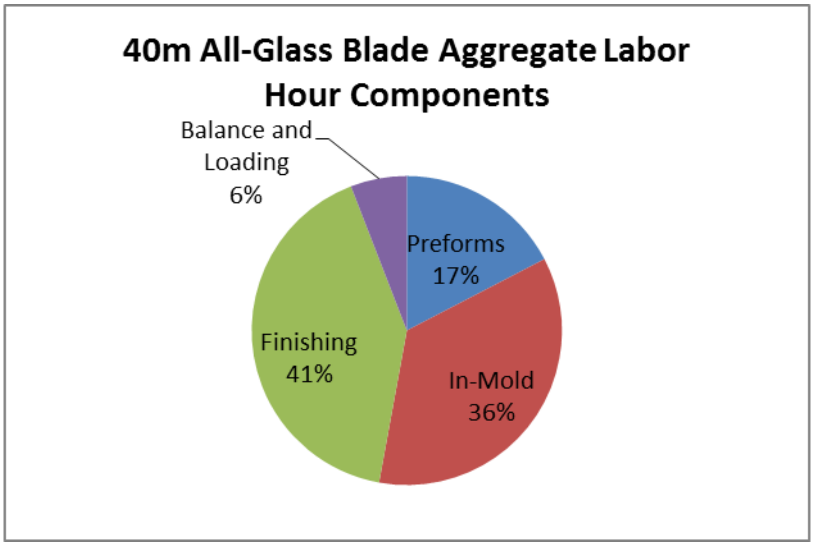

Figure 3. 40m All-glass Blade Labor Content (by Major Operations)

Capital Equipment

The chosen method for blade construction requires a mold for the HP and LP blade skins and the component preforms (e.g. spars, trailing edge). The skin molds are the major individual cost component and scale with blade surface area. Master, mold, and tooling costs were assumed from values provided by industry.

The typical on-shore blade production rate was based on the 24hr process model used in recent blade manufacturing studies. The number of blades produced is an amount over the lifetime of the molds and tooling which is assumed to be three years. See Table 1. The yearly production rate is similar to the estimate projected in the 2003 WindPACT "Cost Study for Large Wind Turbine Blades".

Table 1. 40m Blade Capital Equipment Baseline Costs

R (m)	S (m^2)	Master and Mold Costs	Tooling Costs	Total Cost ($/mold)	Throughput (Blades/Mold)	Cost ($/Blade)
40	166	$1,446,433	$1,590,480	3,036,913	750	4,049

Total Cost

Figure 1 provides a breakdown of costs for the 40m blade for the three major cost components of this model. More than half of the manufacturing cost can be attributed to the materials. Labor constitutes the second largest manufacturing cost and capital equipment is the smallest.

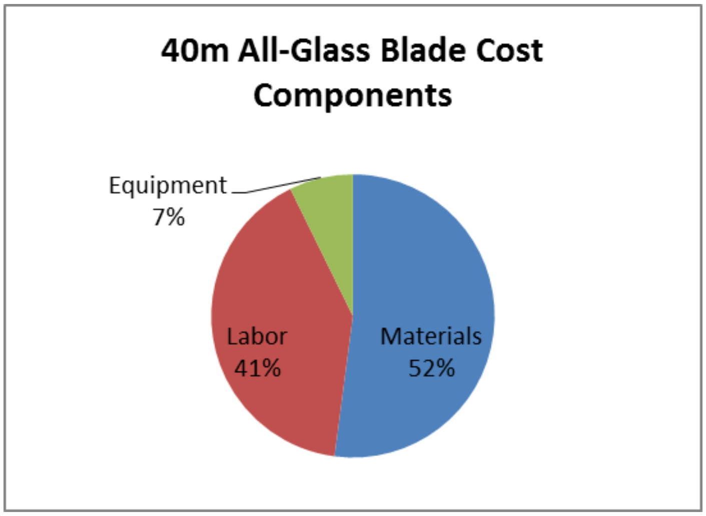

Figure 4. 40m All-glass Blade Major Cost Components Breakdown

100m wind blade manufacturing cost analysis

The 100m blades are assumed constructed as a clamshell blade using VARTM infusion with several preform components. This analysis builds upon the baseline 40m labor process described in the previous sections; however, the materials input is derived from an actual design process wherein laminates are selected and sized based on loads and safety factors defined in international blade design standards.

Case 1: All-glass 100m blade (SNL100-00)

The 100m fiberglass blade (SNL100-00, Reference 5) had preforms for the HP and LP spar caps; three shear webs (fore, center, and aft webs); root; and trailing edge reinforcement. The design is similar to the 40m blade with certain differences. The shell and shear web remain sandwich constructions with bias-ply fiberglass skins and foam cores, but the cores have substantially increased in thickness. The 25.4mm average thickness core has become a 60mm average. The spar caps remain solid unidirectional fiberglass. The root remains bias-ply and unidirectional construction. Prefabricated trailing edge reinforcements were added in place of the wet lay-ups of the 40m blade. They are similar to the construction of the spar caps but have additional foam added on top. The greatest feature change is the design of the spar. The 100m blade uses a double shear web box-beam type spar with a third auxiliary shear web in the trailing edge section. The shear web closest to the leading edge is in the 'fore' position and the next one behind is the 'center' shear web. The third shear web located toward the trailing edge is in the 'aft' position and extends from the near max-chord to the 60m point. The aft shear web has no spar caps.

Materials

The materials considered for this analysis were those chosen for the Sandia 100m Baseline Blade, SNL100-00. The mass of each component was determined from that design. The foam area was determined in the same way as the 40m blade with all three shear webs and the section of TE foam added. The area of the shear webs was estimated from the thickness of the airfoil sections and their length. The blade design is not extensively optimized so the large weight can be somewhat attributed to overdesigned components. A breakdown of material costs by material type for the SNL100-00 blade is provided in Figure 5.

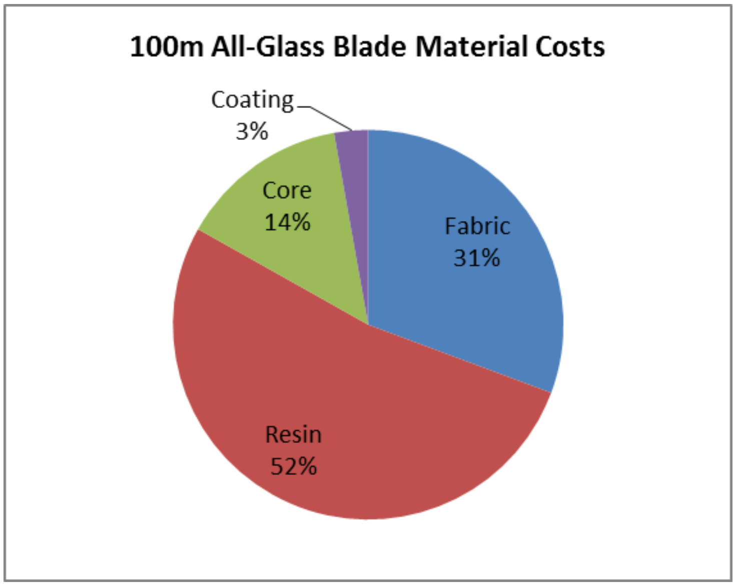

Figure 5. 100m All-glass Blade Materials Cost Breakdown by Material Type

Labor

Labor content for the 100m blade has been extrapolated from data for the detailed, conceptual 40m blade labor content. Increases in labor hours for individual subtasks were informed by specified scaling changes in the component dimensions. The underlying assumption of the labor hours increase was that for a blade length driven subtask operated by two people, the process time for those people would scale according to blade length itself. A blade of twice the length would take twice as long for the same number of people to complete that specific length-driven subtask. All subtasks were analyzed for their driving dimension from which a scaling factor was developed and applied to the 40m blade process – as described in the preceding sections.

Blade skins

Operations for skin lay-up were increased based on surface area. Surface area was chosen because the amount of plies in the skin remains equivalent to the 40m blade. If additional plies were needed then an additional scaling factor for number of plies would have to be multiplied with the surface area scaling factor. Surface area as the driver for labor-hours of the skin ply lay-up was chosen due to the extensive smoothing and aligning that must take place over the entire surface of the lay-up. Mold prepping of the skin mold was also increased based on mold surface area.

Preforms

Root, spar cap and trailing edge (TE) preform lay-up labor hours were scaled based on total ply length. In the case of the root, spar cap, and TE preforms, total ply length was determined to be the driver of labor hours instead of mold surface area. This is due to the molds being very linear and without substantial width changes. In these cases the fabric can be simply unrolled onto the mold from a cart. There is little need for adjustment to the position of the fabric and smoothing is minimal unless substantial curvatures are encountered, which are not seen on the 100m blade. The spar cap of the 100m blade remained a constant width, which was chosen to allow for a simplified manufacturing process. Plies for the spar cap can be supplied directly from the manufacturer on rolls of a nominal width and simply unrolled onto the mold. A spar cap of changing width would require additional cutting of the fabric. An advantage of using a constant width spar cap is that the assumed 40m blade spar cap is also constant width, therefore the process is similar and the scaling is directly attributable to total ply length.

The 40m blade was assumed to have no TE preform operation, so labor data from the spar cap was used to create scaling factors for the similarly sized 100m TE preform. Shear web lay-up labor hours were based on mold length. This is because a similar number of skin plies to the 40m blade were used and the lay-up is very flat so smoothing is at a minimum.

Additional labor hours for all molds were included for consumable lay-up and debagging based on mold length because the operations are limited to the edges of the molds. Mold prepping was based on mold length instead of surface area for these molds because they are very narrow.

Other Labor Operations

Other operations such as drop tests and installing of prefab components were assumed to not increase because the process is the same as that of a 40m blade. Labor hours for applying bond paste to the shear webs and bond-lines was increased based on length of the bonds lines. Bond line length for the leading and trailing edges was determined by totaling the length of the perimeter of the blade. Shear web bond line length was determined by totaling the length of each shear web.

Infusion

Infusion times were increased slightly to reflect volume, but this may not be needed depending on the infusion process (e.g. if additional ports are used and wetting is consistent). The spar cap infusion time was increased by 1.5 man hours over the 40m blade. Curing times were increased a small amount based on part thickness, but the exact relationship is unknown. Curing times for the bond lines and completed skins were not increased because the thick components were already cured.

Finishing

Finishing edge trim, wet-lay-ups, and Bond O work was based on length of the bond line. Finishing operations like sanding, painting, inspection were increased based on surface area. Balancing and loading operation labor hours were not increased.

Analysis

When labor hours are compared to a typical on-shore blade, the main difference can be seen in operations that are driven by surface area. Paint-prep and paint become the major contributors to blade labor hours.

The labor content by subtask for the SNL100-00 blade is provided in Figure 6. And, the labor content by major operations is provided in Figure 7.

Again, the assumed scaling factors for the 40m to 100m blade length change are described above as based on geometric scaling. The tool is quite flexible to allow for modifying these scaling exponents based on proposed process changes to a design or perhaps calibration of the subtask values to actual process data. The aggregate labor scaling factor produced using the above described scaling factors is somewhat low compared to other studies. Changes to the scaling factors can be evaluated easily with the flexibility built into the tool.

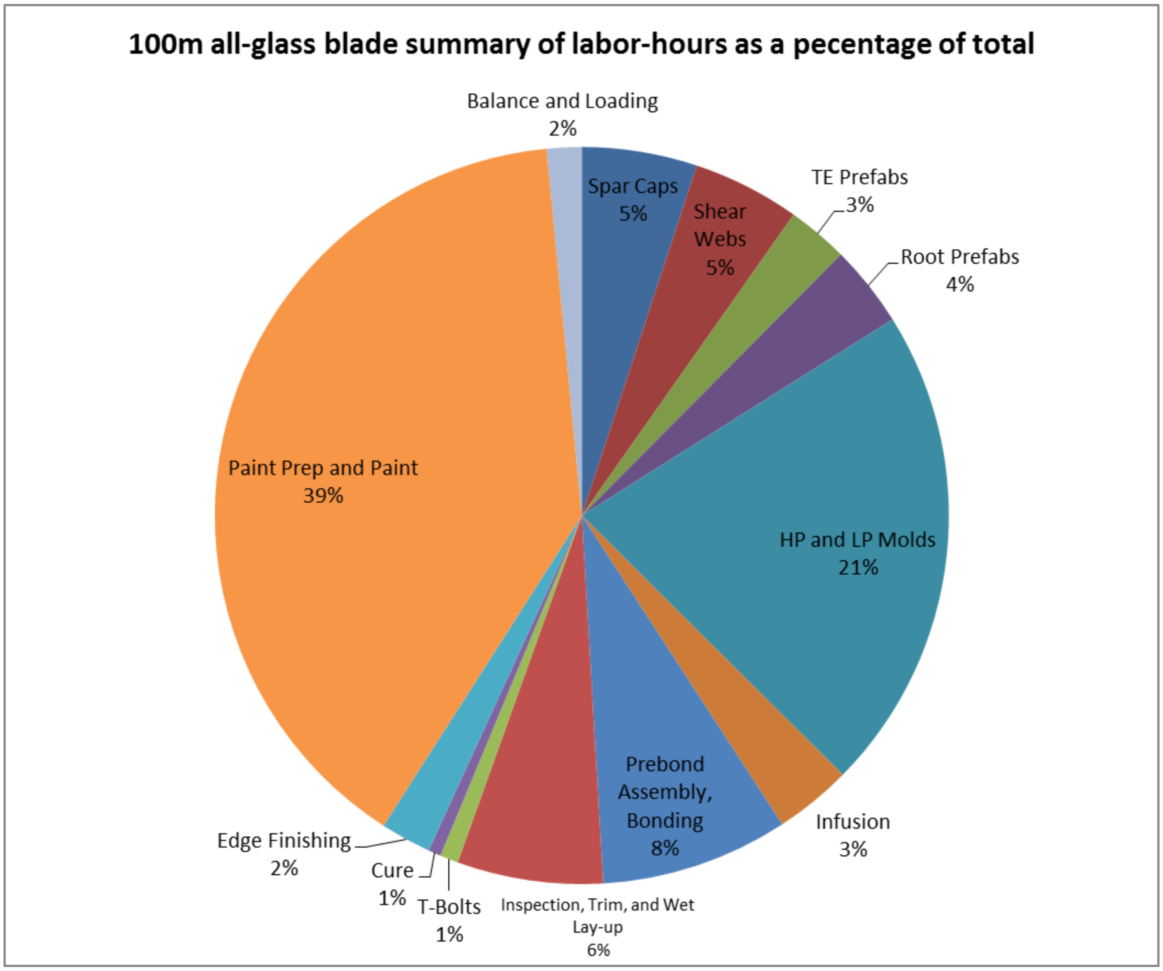

Figure 6. 100m All-glass Blade Labor Content (by Subtasks)

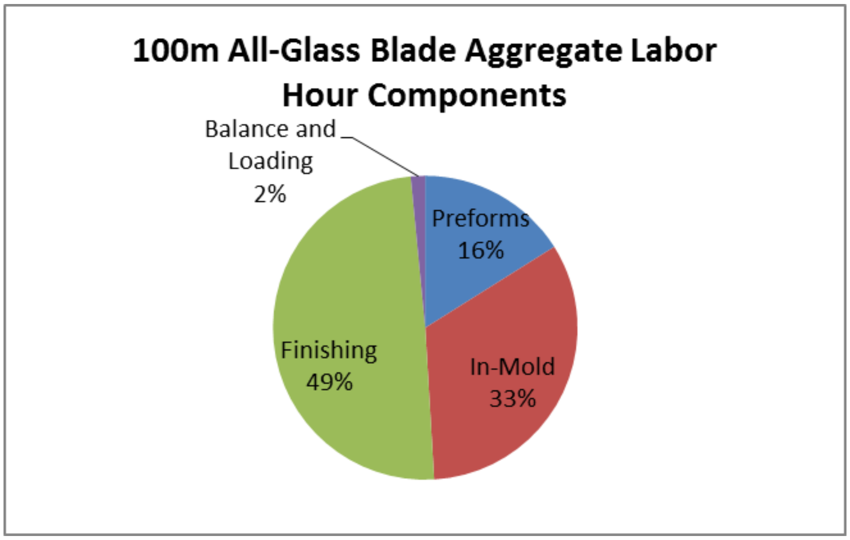

Figure 7. 100m All-glass Blade Labor Content (by Major Operations)

Capital equipment

The chosen method for blade construction requires a mold for the HP and LP blade skins and the seven preforms. The skin molds are the major cost and scale with blade surface area. Capital equipment cost is equal to $(\frac{R2}{R1})^{2.09} \times Cost_{R1}$. This equation was taken from the 2003 WindPACT "Cost Study for Large Wind Turbine Blades" (Reference 3).

A lower blade production rate was assumed. The typical on-shore blade production rate was based on the 24hr process model. The production rate for the 100m blade was assumed to be 1/3 of that. The number of blades produced is a total over the lifespan of the molds and tooling which is assumed to be three years.

Table 2. 100m Blade Capital Equipment Costs versus 40m Baseline

R (m)	S (m^2)	Master and Mold Exponent	Total Cost ($/mold)	Throughput (Blades/Mold)	Cost ($/Blade)
40	166		3,036,913	750	4,049
100	1241	2.09	20,612,328	225	91,610

Total Cost

The largest contributor to the cost of the blade is again the materials with an increase in % total cost. Labor value was assumed to be $30/hr. The labor costs did not escalate with the materials because many manufacturing operations were not scaled at the same rate as weight. Weight increased by 15.7x and labor by 3.8x (See Table 1). Many operations were unchanged in labor content and many scaled primarily with length instead of amount of material. Equipment cost increased by almost 23x, which is a result of much more expensive tooling and a reduced production rate. Because of this, the second highest contributor to total cost becomes the molds and tooling instead of the labor. Figure 8 provides another view of the major costs breakdown for SNL100-00.

Table 3. Cost Components Comparison (40m to 100m All-glass Blade)

100m All-Glass Blade		
Cost Component	% Cost/Blade	x40m
Materials	71.90%	15.74
Labor	13.64%	3.83
Equipment	14.45%	22.62
Total		11.40

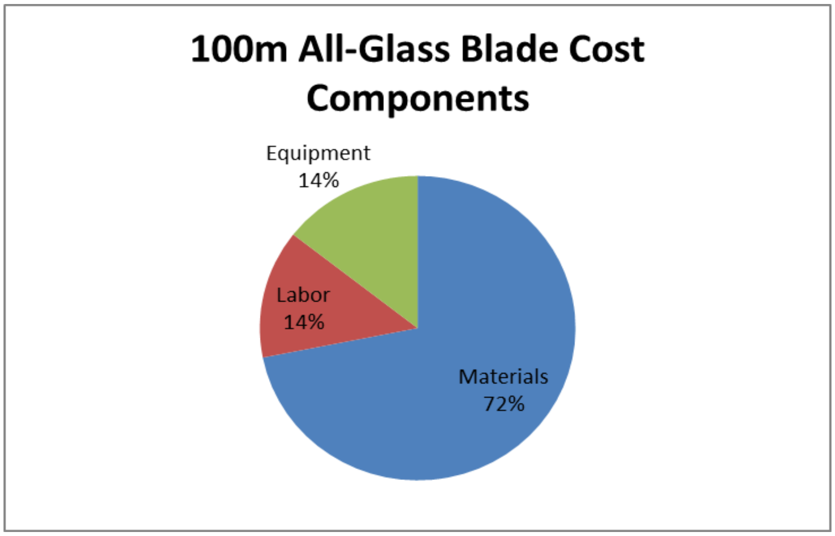

Figure 8. 100m All-glass Blade Major Cost Components Breakdown

Case 2: 100m carbon spar cap plus foam blade

The second example blade study is a 100-meter carbon spar blade, based on SNL100-00. The carbon spar plus foam blade replaces the fiberglass spar caps with ones constructed of carbon fiber and foam. The spar caps are thinner and require foam in the laminate to thicken them to prevent buckling. The addition of foam to the spar cap laminate in an unbalanced fashion creates several interesting manufacturing considerations. The 100m carbon spar cap blade will have preforms for the HP and LP spar caps; fore, center, and aft shear webs; root; and trailing edge reinforcement. This blade design is described in more detail in References 6 and 7.

Materials

The introduction of carbon fiber reduces the cost of fiberglass but increases the use of foam, which is the most expensive component. Additionally, the carbon fiber is nearly nine times more expensive than the fiberglass (dry) it replaces, but not 1/9 of the mass. A breakdown of material costs by material type for this 100m carbon spar with foam blade is provided in Figure 9.

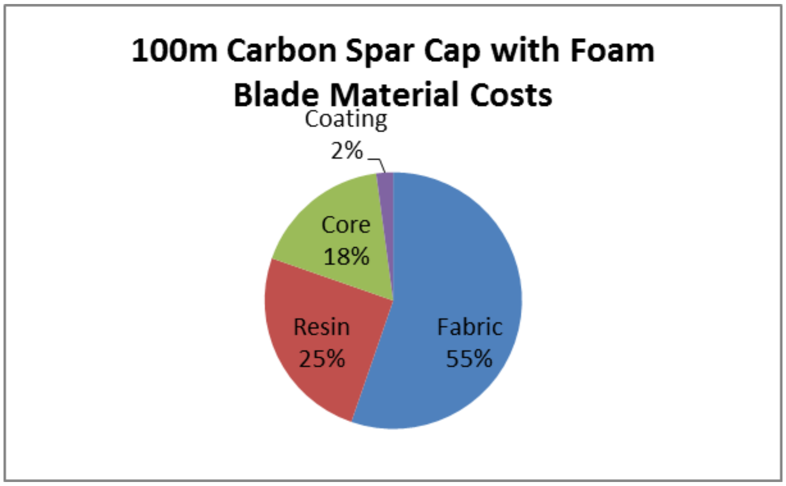

Figure 9. 100m Carbon/foam Spar Blade Materials Cost Breakdown by Material Type

Labor

Most processes for the blade construction remained the same for labor hour content moving from SNL100-00 to this Case 2 blade. Increases were made for the foam installation onto the spar and additional time for inner skin lay-up. Time reductions were made for the carbon spars due to less plies and no infusion preparation since the use of pre-preg fabric has been assumed. The width of the spar cap also decreased but it remains a constant width so no adjustment was needed based on the process assumptions described in the all-glass blade section.

Blade shells

The manufacturing process for the blade shells remains largely the same as the 100m all-glass blade. The only major difference is the inclusion of additional foam on top of the carbon spar caps. The foam to be added is very thick; therefore, considerations were made for this specific addition. In the HP and LP molds section an additional operation was added for "Spar Cap Foam" which totaled four labor hours. Additional time of eight man-hours for the lay-up of the final skin plies on top of the foam was added to the "Final Skin Plies" operation.

Preforms

All preforms except the spar caps remained the same. The labor hours for the spar cap were changed to reflect the use of pre-preg carbon fiber instead of dry fiberglass and an infusion process. The infusion time was eliminated and consumable lay-up was decreased by 1.5 man-hours from the 100m all-glass blade to account for not needing infusion equipment.

Labor hour increases follow the 100m all-fiberglass blade. Operations that involve surface area become a much larger portion of the overall manufacturing time.

The labor content by subtask is provided in Figure 10. And, the labor content by major operations is provided in Figure 11.

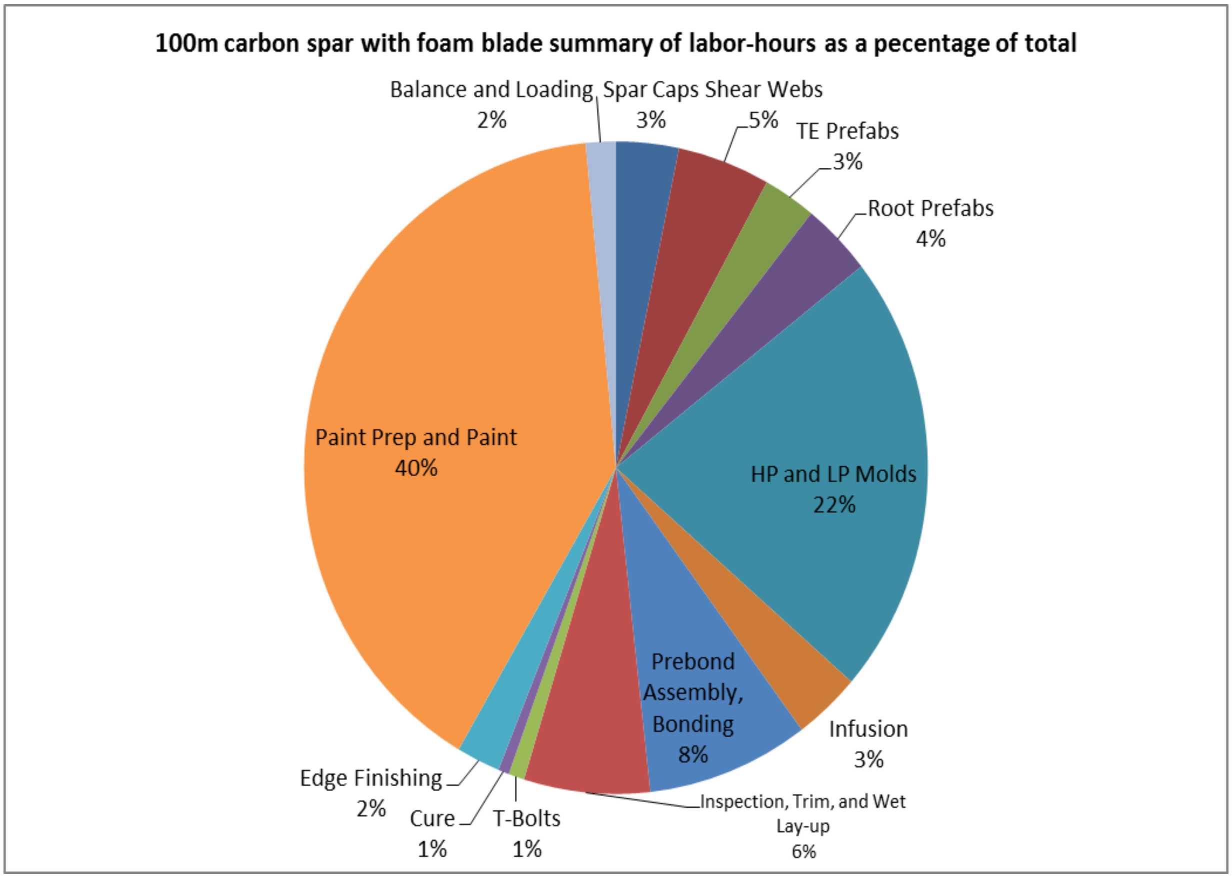

Figure 10. 100m Carbon/foam Spar Blade Labor Content (by Subtasks)

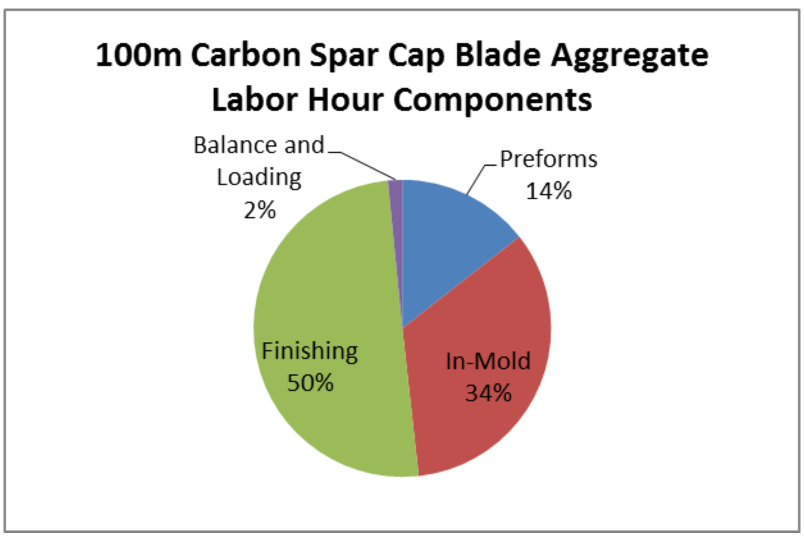

Figure 11. 100m Carbon/foam Spar Blade Labor Content (by Major Operations)

Capital equipment

For the carbon spar blade the capital equipment costs are equivalent to the all-glass blade because the same number and type of molds are used. The same calculations from the all-glass blade were used to determine the mold and tooling costs for the carbon spar plus foam blade.

Total Cost

The carbon spar cap blade was more expensive than the all-glass blade entirely due to material costs. The labor and equipment costs were similar for both, but the addition of expensive carbon fiber and foam substantially increased cost of manufacturing. The carbon fiber and foam also increased the share of material costs by 5% share of the total over the fiberglass blade (see Table 4 and Figure 12).

Table 4. Cost Components Comparison (40m to 100m Carbon Spar with Foam Blade)

100m Carbon Spar with Foam Blade		
Cost Component	% Cost/Blade	x40m
Materials	77.17%	20.72
Labor	11.06%	3.81
Equipment	11.78%	22.62
Total		13.99

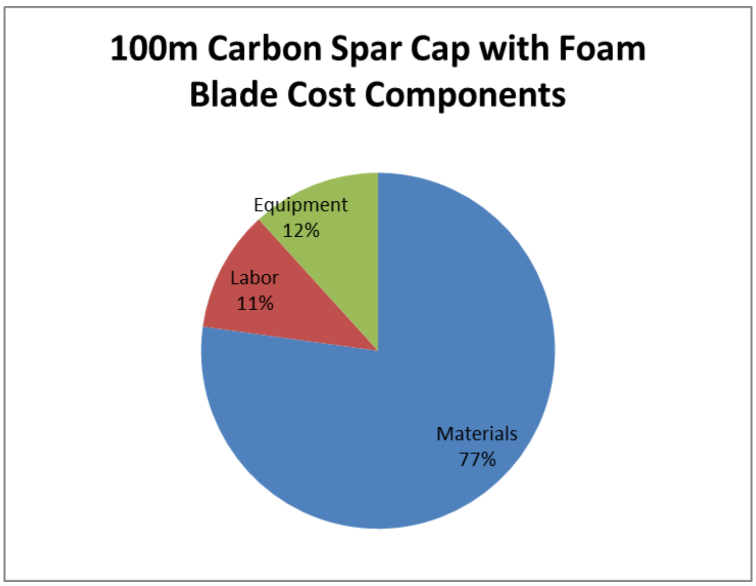

Figure 12. 100m Carbon/foam Spar Blade Major Cost Components Breakdown

Case 3: 100m carbon spar blade (SNL100-01)

The third example case is the final 100m carbon design, termed SNL100-01. This is a carbon spar blade no foam in the spar. The SNL100-01 carbon spar cap blade is a more refined lower weight design compared to the 100m carbon spar plus foam blade. The design details for this blade are provided in Reference 7.

Materials

A breakdown of material costs by material type for the SNL100-01 blade is provided in Figure 13.

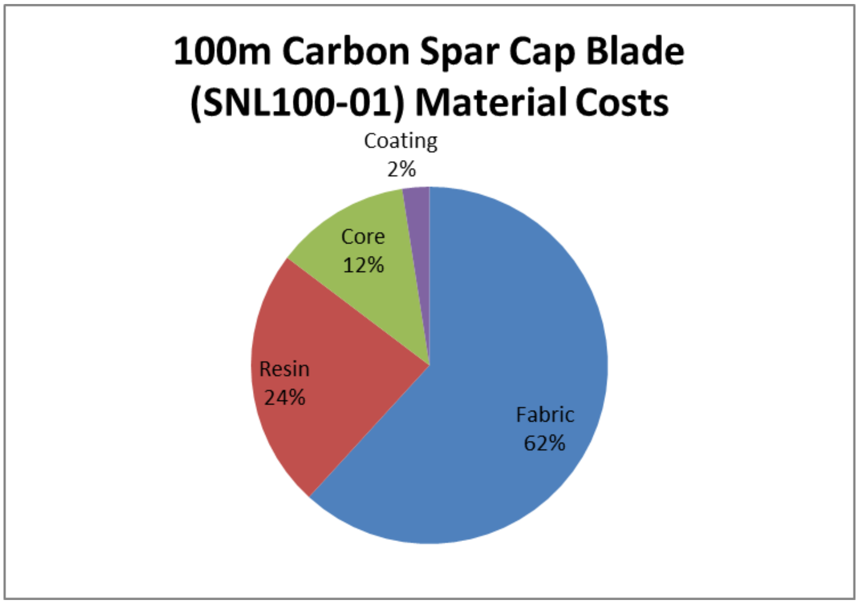

Figure 13. 100m Carbon Spar Blade (SNL100-01) Materials Cost Breakdown by Material Type

Labor

The Labor process was same as discussed in Case 2.

Capital equipment

The Capital equipment costs are also the same for SNL100-01 because the same number and type of molds are used.

Total Cost

The carbon spar cap blade (SNL100-01) was more expensive than the all-glass blade entirely due to material costs. The labor and equipment costs were similar for both, but the higher cost of carbon compared to glass (for assumed price points in this analysis) was the driving factor for the increased cost of manufacturing. See Table 5 and Figure 14.

Table 5. Cost Components Comparison (40m to 100m Carbon Spar Blade)

SNL100-01 Carbon Final		
Cost Components	% Cost/Blade	x40m
Materials	74.85%	18.25
Labor	12.18%	3.81
Equipment	12.97%	22.62
Total		12.70

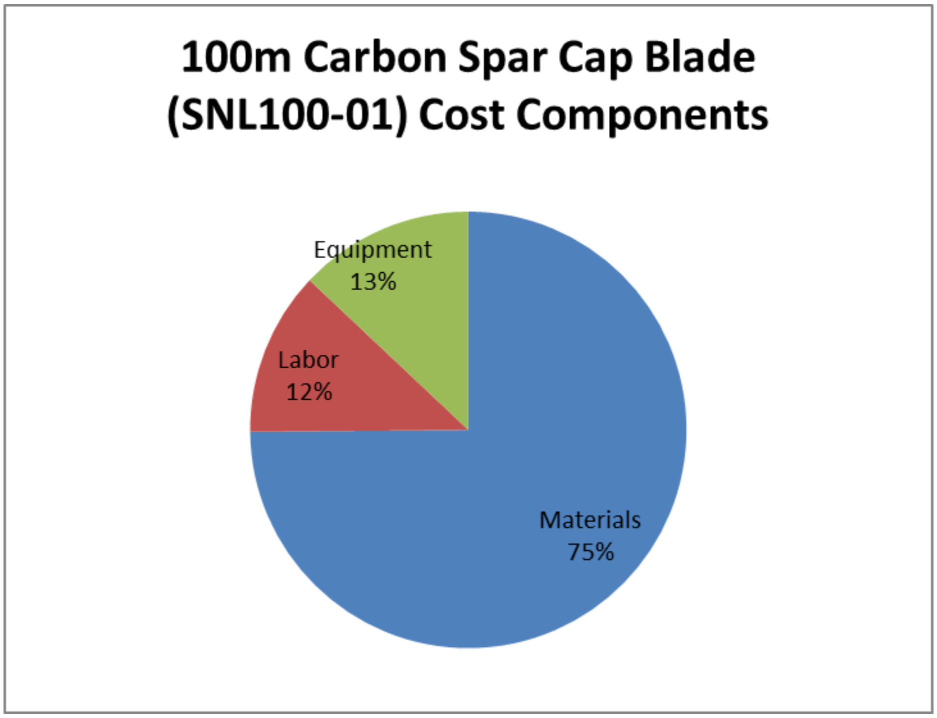

Figure 14. 100m Carbon Spar Blade (SNL100-01) Major Cost Components Breakdown

COSTS SENSITIVITY ANALYSIS

An analysis of several variables was conducted to assess the impact of changes to the automation level, wage rates, and capital equipment cost. This was done to provide an example of how the model can be manipulated to simulate certain changes in the manufacturing process and how they affect the overall blade cost.

Automation

To simulate the addition of automation, specific subtasks were chosen to be replaced with a fully automated process. The method of analysis was to reduce the labor hours for both the 40m and 100m blade subtasks. This was accomplished by reducing the number of operators and the process time. The labor savings per blade was reflected in the labor cost. That labor savings was multiplied by the total lifetime blade production for that mold set. The resulting value was equal to the maximum amount that could be spent on automating a mold set provided that the production rate did not change. Another estimate was modeled using an assumed capital equipment cost for automation. This provided a minimum number of blades that would need to be produced on that mold set over its lifetime to justify the automation costs.

Example 1: Spar Cap Automation

The first example to be examined was the spar cap lay-up subtask. This operation is primarily linear in nature since the fabric is unrolled back and forth down the length of the mold. Therefore it was assumed that this process would be a strong candidate for automation. The lay-up times for both the 40m and 100m all-glass blades were reduced by approximately six times to reflect a faster process and the number of operators was reduced to one person to oversee the automatic process. The resulting labor savings showed that a 100m blade has two times the lifetime savings of a 40m blade assuming no productivity increase. The much higher number of plies in the spar cap of the 100m all-glass blade requires over six times as much labor which provides a greater budget for additional equipment to automate the work than the thinner 40m spar cap. The model also includes inputs for proposed automation solution costs in the "Assumed CAPEX Value" projection. The impact of these costs can be realized in the productivity increase required to offset the automation equipment cost.

Table 6. Example Spar Cap Preform Automation Cost Trade-off

Spar Cap Preform Lay-up Automation Analysis				
Blade	Scenario	Cost Savings/Blade	Automation CAPEX (Cost/Mold Set)	Three Year Production Rate (Blades/mold)
40m All-Glass	Assumed CAPEX Value	$324.00	$1,000,000.00	3,086
	Assumed Production Rate	$324.00	$243,000.00	750
100m All-Glass	Assumed CAPEX Value	$2,136.00	$2,500,000.00	1,170
	Assumed Production Rate	$2,136.00	$480,600.00	225

Example 2: Paint Prep and Paint Automation

The paint prep and painting operation was also deemed a strong candidate for automation due to the massive increase in labor hours that occurs when scaling from a 40m to a 100m blade as this operation is driven by area scaling. To reduce the process time of this operation, more people must be added which increases the exposure of laborers to an undesirable and potentially hazardous job -- unless an automated solution can provide the same reduction. Because the subtasks of this operation are so closely tied to the surface area, all of them were reduced by approximately 6.5 times for both the 40m and 100m blades. The people required was also reduced to one operator to oversee the process. The labor savings once again showed that the 100m blade allows for about two times the savings for the 100m over the 40m blade. The value of the savings was also relatively high, which suggests that incorporating automation for this process may be more economically feasible than other processes. The model also provides a projection of the productivity increase required to offset the expense of a potential automated solution.

Table 7. Example Paint-Prep and Paint Automation Cost Trade-off

Paint and Paint Prep Automation Analysis				
Blade	Scenario	Cost Savings/Blade	Automation CAPEX (Cost/Mold Set)	Three Year Production Rate (Blades/mold)
40m All-Glass	Assumed CAPEX Value	$4,260.00	$4,000,000.00	939
	Assumed Production Rate	$4,260.00	$3,195,000.00	750
100m All-Glass	Assumed CAPEX Value	$29,074.25	$10,000,000.00	344
	Assumed Production Rate	$29,074.25	$6,541,706.25	225

Wage Rate

The wage rate was adjusted by ±25% to account for differences in labor rates for different areas or inaccuracies in the assumed rate. This was done by simply adding or subtracting 25% to the average wage rate that was assumed in the model for each blade design. The result concluded that the smaller blades are more sensitive to fluctuations in wage rate, which agrees with the labor percentage component of the different blade designs.

Table 8. Labor Cost Sensitivity to Wage Rate

Blade	Baseline Labor Cost per Blade	Labor Cost Reduced by 25%	Labor Cost Increased by 25%
40m All-Glass	40.63%	33.92%	46.11%
100m All-Glass	13.64%	10.60%	16.49%
100m Carbon Spar with Foam	10.95%	8.45%	13.33%
100m Optimized Carbon	11.85%	9.16%	14.39%
61.5m Carbon Spar	19.94%	15.74%	23.74%

Capital Equipment Cost

The sensitivity analysis was conducted in a similar manner to the wage rate. An increase and decrease of 25% was included in the total cost assumptions for the capital equipment value for each blade design. The results show that larger blades are more susceptible to increases in capital equipment costs.

Table 9. Capital Equipment Cost Sensitivity

Blade	Baseline Equipment Cost per Blade	Equipment Cost Reduced by 25%	Equipment Cost Increased by 25%
40m All-Glass	7.28%	5.56%	8.94%
100m All-Glass	14.45%	11.24%	17.43%
100m Carbon Spar with Foam	11.79%	9.11%	14.31%
100m Optimized Carbon	12.76%	9.88%	15.45%
61.5m Carbon Spar	7.77%	5.95%	9.53%

Carbon Fiber Feasibility

Another use of this model is to examine price points that make use of advanced materials feasible. For example, if carbon fiber is to be used in any extensive capacity in the blade construction, the material cost of the blade increases by a large margin over an all-glass blade. It increases the material cost to such an extent that an overall weight reduction of over 20% from initial carbon spar cap blade designs (a 41% reduction from the all-glass concept) would be required to produce a similarly priced blade. The possibility of an optimization effort resulting in that level of mass reduction may not be feasible. However, if the price of carbon fiber were to be reduced by increased production levels of wind energy specific fabrics or a new cheaper fabric with slightly reduced performance, the potential for its use would rise substantially.

Additional study on the feasibility of carbon is provided in Reference 8 along with a summary description of the SNL100-01 design and this cost analysis tool.

The analysis to gauge the impact of a carbon fiber price reduction was simple. The price of the carbon fiber was reduced until the material cost of the carbon spar cap blade was equal to the all-glass variant. The required price reduction of the carbon fabric was over 34% from the assumed value. The possibility of such a price reduction may be unlikely, but a combination of material mass optimization in the design and price reduction may allow carbon fiber to be more economically feasible for future blades.

ENERGY PRODUCTION FACTORS

The total manufacturing costs for the 100m blade designs are 11.4 times more for the all-glass blade and 12.7 times more for the carbon spar blade. When considering the feasibility of these costs at a systems level, an analysis of annual cost of energy is required.

The components of the cost of energy analysis combine to provide a levelized yearly cost per kilowatt-hour for an on-shore 40m turbine, an off-shore 40m turbine, and the 100m off-shore turbine. Included in this calculation were the initial capital costs (ICC), fixed charge rate (FCR), levelized replacement cost (LRC), and levelized operations and maintenance (O&M). The 40m blade turbine was classified as a 1.5MW turbine and the 100m blade turbine was classified as 13.2MW. Obviously the intended location wind class and blade weight heavily influence the generating potential, but these were not factored into this initial analysis. The capacity factor of the potential site can be altered to provide a measure of performance based on location and turbine design factors like cut-in speed.

Blade Design Comparison

Due to the method of the calculation in this table, the ability to easily compare the COE impact competing blade designs for a turbine with the same energy output is not straightforward. The cost of the turbine is only presented as a total cost for all components based on potential energy production. To incorporate the change in blade value, the cost of the blade was multiplied by three blades per turbine and divided by the potential energy production value. This gives the cost per kW of the blades. Since no baseline 100m blade value exists, it was determined to be an average of the 100m blades chosen for the analysis. This value was assumed to be the blade cost component of the ICC for the 13.2MW turbine. The rotor costs were subtracted from the baseline to give a value of cost saved per kW. It is also assumed that a reduction in the weight of the blade leads to reductions in the cost of the other turbine components like the tower and foundation. Therefore, the percent weight savings of each blade design was multiplied by the turbine cost, raised to the 0.5 power to reflect a non-one-to-one ratio of blade weight savings to cost savings, and added to the cost of the turbine. The cost savings for each turbine design was subtracted from the ICC cost/kW.

Wind Farm Comparison

A comparison was made of three potential 250MW wind farms: one on-shore made up of 1.5MW turbines, one off-shore made up of 1.5MW turbines, and one off-shore made up of 13.2MW turbines. Data from Appendix B of “NREL 2010 Cost of Wind Energy Review” report was used to calculate the capacity factor, ICC, FCR, LRC, and O&M rates for on- and off-shore turbines. Initial capital cost was calculated as a multiple of maximum potential energy production.

Operation and Maintenance Value

To further decrease the COE for a larger turbine farm O&M cost must be reduced, but the method of calculation in this analysis does not provide for that. A reduction in O&M makes sense due to the drastically lower number of turbines that are required to be monitored and maintained. The value for O&M cost determination provided by the DOE was based on cost per potential energy output. This method may incorrect based on the type of O&M that is provided. The O&M cost per turbine when comparing a 1.5MW off-shore turbine to a 13.2MW turbine is nearly nine times larger for the 13.2MW machine. This seems to be overstated considering the already high cost of maintenance for off-shore wind farms. O&M cost for a 250MW wind farm is three times higher for a wind farm of nineteen 13.2MW units compared to a farm of 167 1.5MW units. The cost of maintaining 8.8 times as many off-shore turbines should not be substantially cheaper than maintaining a very small farm of larger turbines. If O&M cost for the 13.2MW is assumed to be to the on-shore cost/kW of a 1.5MW turbine (equating to a 66% reduction in O&M cost) then the COE for the larger turbine becomes a larger advantage.

Results

A simple initial analysis of the resulting COE comparisons showed that an equal sized off-shore farm with 1.5MW turbines triples the cost of energy from an on-shore farm. The 13.2MW turbine farm had 8.8 times fewer turbines and 9 times higher O&M costs per turbine, but it had slightly lower COE compared to the 1.5MW turbine off-shore farm. If reductions are assumed to be made to the ICC through weight optimization and manufacturing cost of the rotor then the COE of a larger bladed turbine farm decreases, but only slightly in this example scenario.

Table 10. Example Cost of Energy Comparisons for Wind Farms with 40m and 100m Blades

Blade	ICC ($)	FCR (%/yr)	LRC ($/yr)	O&M ($/kWhr)	O&M ($/turbine)	O&M ($/Farm)	AEPnet (kWhr/yr)	Units/Farm	COE ($/kWhr)
40m On-Shore	3,150,000	0.1	16,500	0.005	22,500	3,757,500	4,995,943	167	0.0709
40m Off-Shore	8,400,000	0.12	60,000	0.013	69,000	11,523,000	5,127,415	167	0.2217
100m Off-Shore	73,920,000	0.12	528,000	0.013	607,200	11,536,800	46,283,491	19	0.2162
100m Off-Shore All-Glass	74,118,812	0.12	528,000	0.013	607,200	11,536,800	46,283,491	19	0.2167
100m Off-Shore Carbon Spar with Foam	73,969,426	0.12	528,000	0.013	607,200	11,536,800	46,283,491	19	0.2163
100m Off-Shore Optimized Carbon Spar	73,546,596	0.12	528,000	0.013	607,200	11,536,800	46,283,491	19	0.2152
Off-Shore with 66% lower O&M	73,920,000	0.12	528,000	0.005	208,445	3,960,452	46,283,491	19	0.2076

FUTURE WORK

To understand the impact of larger blades on the manufacturing process further work must be done in several areas.

- Value of components. The value of individual blade components like prefabricated parts is much higher for a larger blade. For example, just the material value of a single carbon spar cap for a 100m blade is 2.5 times greater than the value of an entire completed 40m blade. If components contain a high value due to the amount of material in them, the increased labor required to produce them, and because fewer will be produced each year, then special attention must be made to manage defects. A scrapped prefab for a 100m blade would be extremely expensive to replace relative to the equivalent part on a 40m blade, especially if carbon fiber is used in the construction. This may lead to considering more expensive aerospace style construction methods and automation to improve quality and reduce defects.
- The potential of automation must be further assessed by adjusting the labor-hours according to the performance of the automated method and comparing it to the cost of implementing it. The analysis provided in this report is merely an example of the potential of the tool, but the true costs and benefits of automating specific subtasks will have to be further considered.
- The cost of energy analysis tool can be refined to provide more accurate assessments of the impact of blade manufacturing cost, weight, and performance.
- This model may be combined with other models that provide cost estimates for other features of wind turbine construction and operation. Doing this will yield a better input into the cost of energy model that correctly accounts for the many changing variables of turbine design.

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