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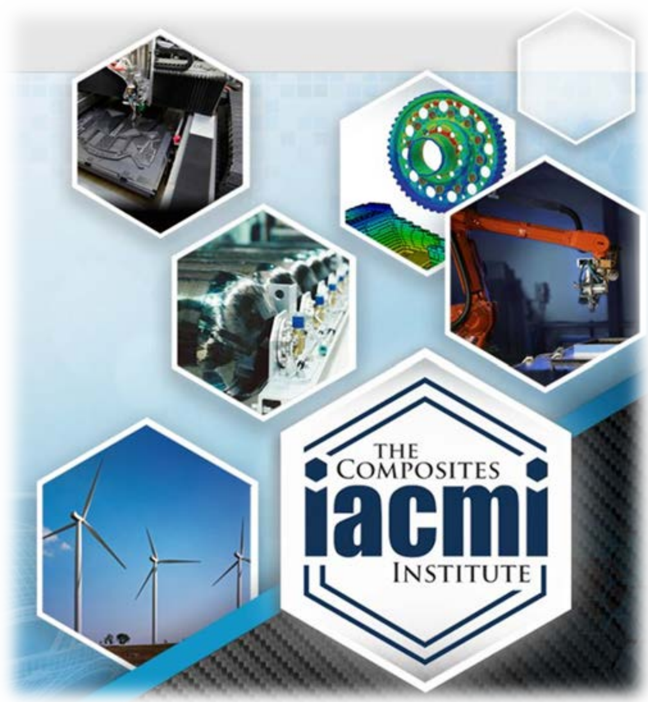
Impact of Technology Developments on Cost and Embodied Energy of Advanced Polymer Composite Components



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The Institute for iacmi Advanced Composites Manufacturing Innovation THE COMPOSITES INSTITUTE

U.S. DEPARTMENT OF ENERGY

Impact of Technology Developments on Cost and Embodied Energy of Advanced Polymer Composite Components

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List of Acronyms

CCS	Collaborative Composite Solutions Corporation
CFRP	Carbon Fiber Reinforced Polymer
CT	Coated Tow
COV	Coefficient Of Variation
FRPC	Fiber Reinforced Polymer Composite
HPRTM	High Pressure Resin Transfer Molding
IACMI	Institute for Advanced Composites Manufacturing Innovation
IOM	Injection Overmolding
MII	Manufacturing Innovation Institute
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PCM	Prepreg Compression Molding
RFF	Rapid Fabric Formation
RTM	Resin Transfer Molding
VARTM	Vacuum Assisted Resin Transfer Molding

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Executive Summary

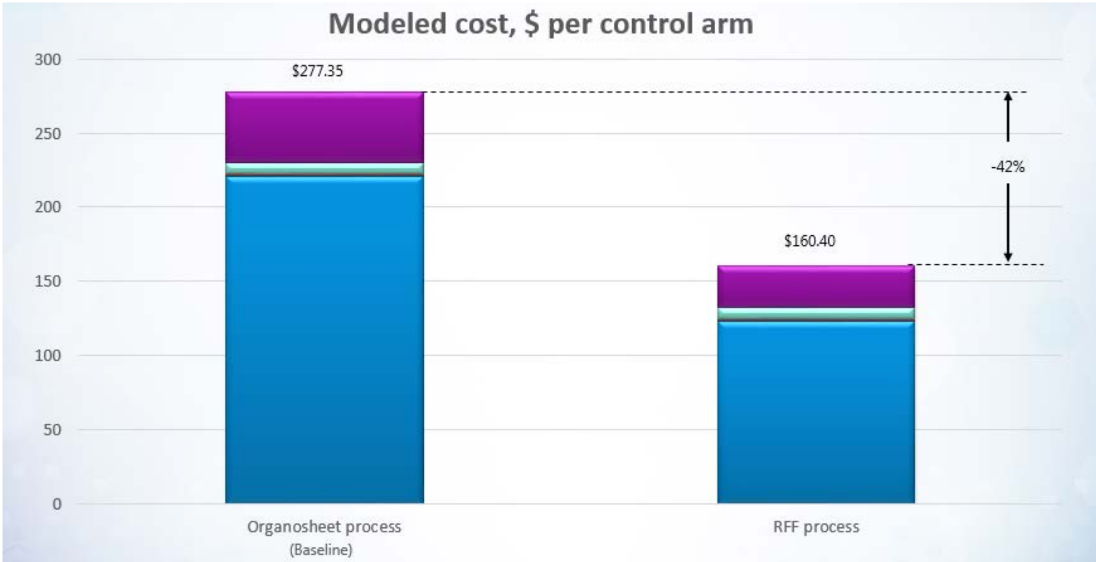
Within Manufacturing USA, The Institute for Advanced Composites Manufacturing Innovation, IACMI, is a partnership of industry, private and state universities, as well as federal, state, and local governments that are working together to benefit the nation's energy and economic security. This diverse public/private partnership validates manufacturing technologies that respond to private industry's need for faster and more cost-, material-, and energy-efficient composites manufacturing, including recycling at the end of product life.

IACMI has set specific quantitative goals towards advancing the state-of-the-art in materials and manufacturing technologies for carbon fiber reinforced polymer matrix (CFRP) composites. The goals were set with respect to three targeted application areas, namely: automobiles, wind turbine blades and compressed gas storage tanks. The specific goals set for IACMI at the end of the first five years were to: (1) reduce the cost of productionized composite parts by 25%, (2) reduce the embodied energy in the production of these parts by 50%, and (3) increase recyclability of CFRP parts into useful products to 80% of the part being recycled.

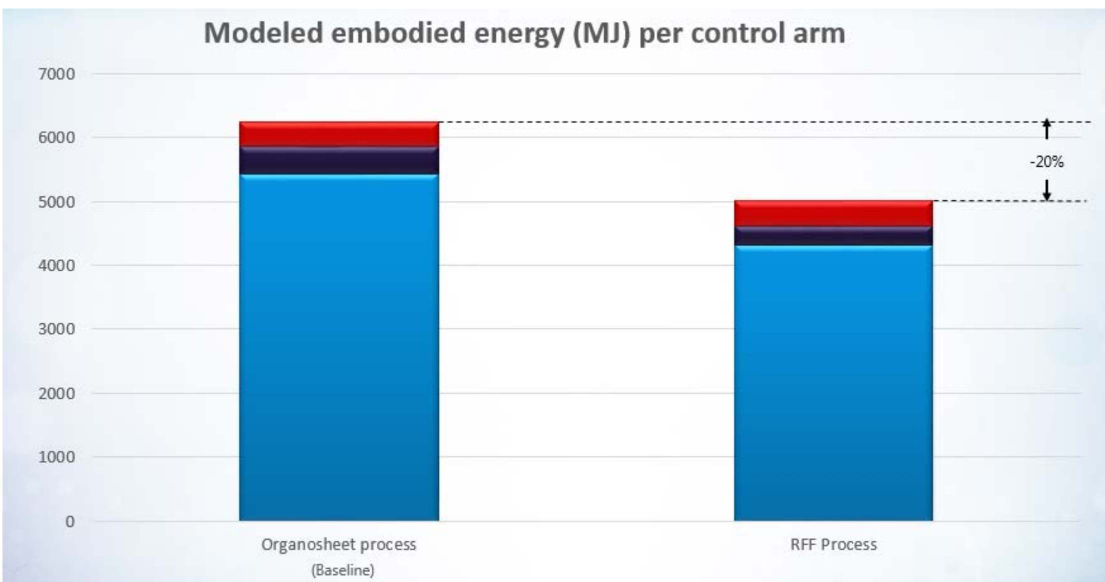
A baseline set of metrics representing the state-of-the-art at the start of IACMI (June 2015) were required to estimate the potential impact of the various technology development efforts towards these goals. Further, the actual impact on the baseline metrics as each project is completed needs to be quantified, considering the technology advances accomplished. These baseline cost and energy metrics are available on the IACMI website at https://iacmi.org/baseline-cost-energy. A special embodied energy estimator tool, developed by Oak Ridge National Laboratory (ORNL), is available to the public online at http://www.energytoolestimator.com/, and has been used to develop the baselines as well as evaluate impacts from completed IACMI projects.

This report describes the impact of two recently completed IACMI sponsored technology projects on the baseline metrics. In the first project, titled "Thermoplastic Composites Parts Manufacturing Enabling High Volumes, Low Cost, Reduced Weight with Design Flexibility", a highly drapable, easily recyclable thermoplastic coated, near net-shape carbon fiber fabric was developed. The thermoplastic coated tow (CT) fabric was manufactured using a rapid fabric formation (RFF) process developed for textile manufacturing. The DuPont, Fibrtec, and Purdue University team that accomplished the development of this low scrap rate carbon fiber product form selected an automobile control arm to be built in a follow-on phase of the project as a demonstrator of the benefits of this technology.

The DuPont-led RFF project showed great promise on several fronts. The flexible tow, combined with near net-shape layup and selective tacking points, allowed for more complex structures and better material utilization versus conventional stiff thermoplastic fabric prepregs (organosheet). This improvement in material utilization is principally responsible for the 20% embodied energy reduction.The resulting scrap reduction and a lower cost carbon fiber fabric material form ($22.04/kg vs $29.75/kg) yield a 42% cost reduction over the baseline process and material, as shown in the following charts:



Control arm cost comparisons



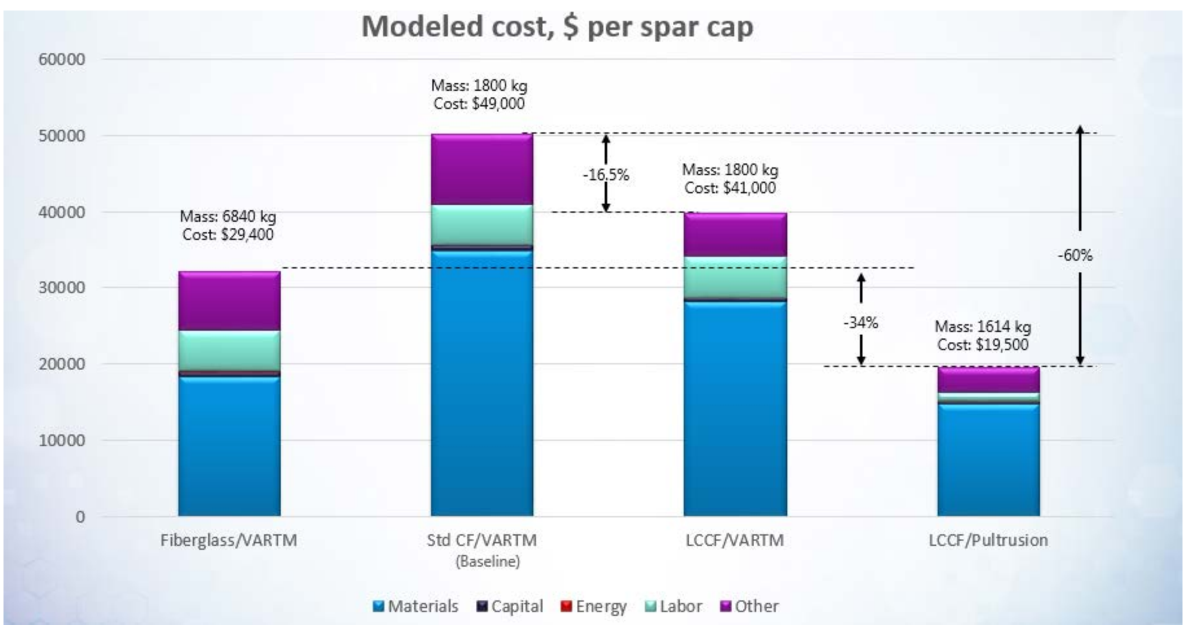
Embodied energy comparison for 5 kg control arm with two different starting product forms.

Further work with this material is recommended, including: detailed design of a complex part like the control arm, prototype molding, and validation of the material properties and improved costs and reduced embodied energy. Results should be compared with incumbent materials and processes, like cast iron or die-cast aluminum, for this application.

The second completed IACMI project was a 9-meter wind turbine blade technology demonstrator incorporating a novel reactive infusion resin that results in a thermoplastic matrix for the skins and shear web, coupled with a pultrusion process for a carbon fiber polyurethane matrix wind blade spar cap using a textile PAN-based carbon fiber developed at ORNL. This pultruded carbon fiber/polyurethane matrix spar cap was analytically scaled up to the 61.5 meter dimension used for establishing the baseline cost and embodied energy.

The pultrusion process, combined with the use of the textile PAN-based carbon fiber (low cost carbon fiber), offers the wind industry the opportunity to overcome a significant cost hurdle preventing widespread use of carbon fiber for utility scale blades. While most producers use fiberglass-based VARTM processed spar caps, several OEM's have specified carbon fiber, with at least one employing standard carbon fiber in pultruded form. As shown in the chart below, the spar cap costs for the baseline 61.5m blade via the VARTM process for traditional carbon fiber and low cost carbon fiber were $49,000 and $41,000, respectively, both a premium over an equivalent fiberglass/VARTM cap at $29,400.By comparison, a pultruded spar cap made from traditional PAN-based industrial carbon fiber (not presented in this report) was approximately $30,000 or just slightly above the fiberglass/VARTM spar cap cost.

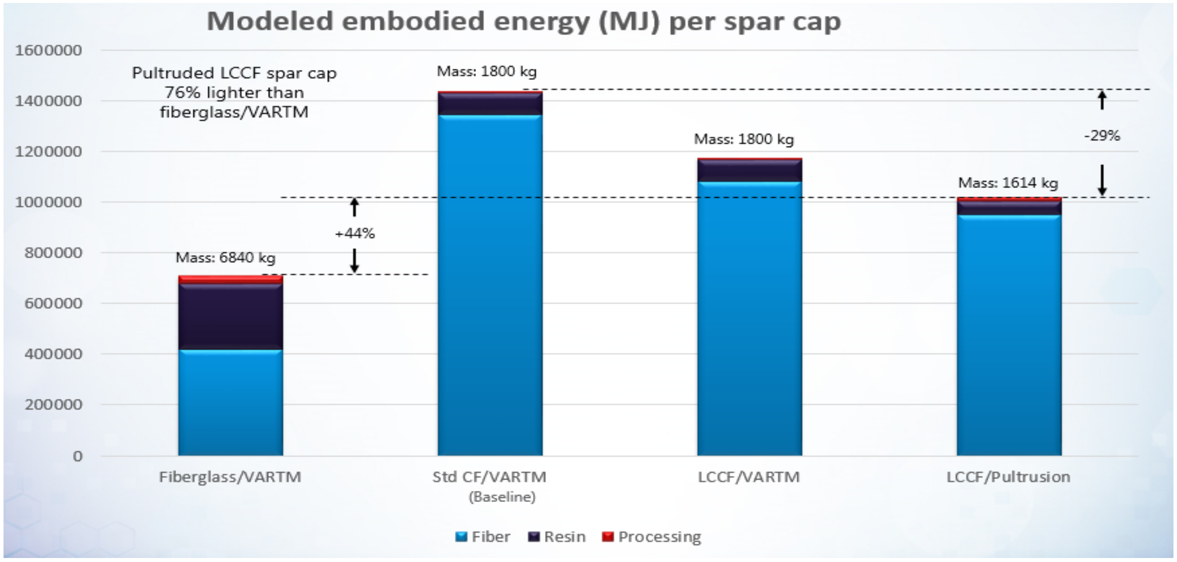
Combining the two innovations detailed herein results in a spar cap cost of $19,500 which was 60% lower than the baseline traditional PAN/VARTM combination and 34% lower than the fiberglass/VARTM option. The key factors contributing to these reductions include the use of a carbon fiber that costs $11.00/kg (versus $17.60/kg) in an as-produced format with no additional weaving cost, a higher fiber volume due to the pultrusion process, lower tooling costs, and significantly lower labor costs resulting from the elimination of layup and bagging of the spar cap.



Comparison of the costs for the various spar cap materials and process combinations evaluated.

The embodied energy of the pultruded low cost carbon fiber spar cap was 29% lower than the baseline carbon fiber version, although still 44% higher than the fiberglass version, as shown below. This gap against fiberglass in absolute terms is intrinsic and cannot be overcome on a per kilogram basis.

However, the actual additional embodied energy this difference represents for a carbon fiber spar cap in a 5 MW turbine that uses a 61.5 m blade is generated within the first three days of operation of the turbine making the difference insignificant over a 20 year operating life of the turbine.



Comparison of the costs for the various spar cap materials and process combinations evaluated.

Experience with using low cost carbon fiber in a pultrusion process is relatively limited, and needs additional development. The pultruded profiles need to be separately tested for mechanical performance, including fatigue, before incorporation into blades to be tested for overall stiffness and blade fatigue life. These are recommended tasks for NREL to pursue. If the advancements demonstrated in the 9m blade project are validated in follow-on projects, the potential cost savings will be very attractive to wind turbine OEMs.

The baseline cost and energy metrics developed by IACMI, the ORNL cost model, and the embodied energy model developed by ORNL should be used on other IACMI projects, as IACMI and industry partners continue to reduce both costs and energy of advanced composites.

Section 1: Introduction

Manufacturing USA is an initiative focused on coordinating public and private investment in emerging advanced manufacturing technologies. Manufacturing USA brings together industry, academia, and government partners to leverage existing resources, collaborate, and co-invest in advancing manufacturing innovation and accelerating commercialization. This network creates a competitive, effective, and sustainable research-to-manufacturing infrastructure for U.S. industry and academia. The network consists of multiple linked Manufacturing Innovation Institutes (MIIs) with common goals but unique technological concentrations.

Within Manufacturing USA, The Institute for Advanced Composites Manufacturing Innovation, IACMI, is a partnership of industry, private and public universities, as well as federal, state, and local governments that are working together to benefit the nation's energy and economic security. This diverse public/private partnership validates manufacturing technologies that respond to private industry's need for faster and more cost-, material-, and energy-efficient composite manufacturing, including recycling at the end of product life. IACMI's research and development programs are driven by major industry participation with a focus on reducing technical risk and developing a robust supply chain to support a growing advanced composites industry.

IACMI broadly engages educational, economic development, trade, and professional organizations to build the skills and workforce critical to the growth of composite industry companies of all sizes. IACMI is managed by Collaborative Composite Solutions Corporation (CCS), a not-for-profit organization established by the University of Tennessee Research Foundation and which operates under contract to the Advanced Manufacturing Office of the Department of Energy's Energy Efficiency and Renewable Energy division.

IACMI has set specific quantitative goals towards advancing the state-of-the-art in materials and manufacturing technologies for carbon fiber reinforced polymer matrix (CFRP) composites. The goals were set with respect to three targeted application areas, namely: automobiles, wind turbine blades and compressed gas storage tanks. The overarching purpose of these goals was to reduce the cost of composites for these targeted applications, develop and demonstrate process technologies that reduce embodied energy in manufactured composite parts, and develop economically viable processes for the recycling and reuse of process scrap and composite parts at the end of their lifetime. The specific goals set for IACMI at the end of the first five years were to: (1) reduce the cost of productionized composite parts by 25%, (2) reduce the embodied energy in the production of these parts by 50%, and (3) increase recyclability of CFRP parts into useful products to 80% of the part being recycled.

The CFRP technology developments envisioned for IACMI could very well be disruptive but the achievement of the quantitative goals is expected to be incremental. A baseline set of metrics representing the state-of-the-art as at the start of IACMI (June 2015) were required to estimate the potential impact of the various technology development efforts towards these goals. Further, the actual impact on the baseline metrics as each project is completed needs to be quantified, considering the technology advances accomplished.

Of the three quantitative goals mentioned in the preceding paragraph, the cost and the embodied energy baseline metric values and their sensitivities were readily established using existing models and tools. This report first explains the establishment of the baseline data for CFRP costs and embodied energy and their sensitivities to various parameters such as material costs, manufacturing processes, and part size. Next, the improvements in these baseline metric values were quantified following completion of a project focused on a low waste, rapid fabric formation process developed by DuPont, and the fabrication of a 9-meter technology demonstration blade, featuring novel in-situ polymerizable thermoplastic polymer and pultruded carbon fiber spar caps. These were assessed using the tools developed for the baseline metrics. Critical to any computation of the baseline or improved metrics using state-of-the-art tools are the materials data, manufacturing process data, and the assumptions made. The data sources and the assumptions made for the calculated metric values and their sensitivities are detailed in this report.

Section 2: Background

Initial State of the Art in Composite Manufacture

During the proposal phase in 2014, and up to the contract award to IACMI June 2015, members of the IACMI proposal team visited leading manufacturers of composite components for the automotive, wind turbine and compressed gas storage markets, which were the three initial markets of focus for IACMI. These discussions centered around materials of construction, process steps and cycle times, material utilization (scrap rates), and on-going developments that could result in improvements in cost, energy and recyclability of composite materials and structures. These values were confirmed during plant tours, where the manufacturing process was observed. The team also interviewed numerous material suppliers, most of whom were candidates to work with IACMI, to better understand products in each manufacturer's "pipeline" that could improve yields, cycle times and costs.

The proposal team also reviewed announcements in the trade press, usually promoted by material suppliers, many of which touted cycle times and performance that were well ahead of what was observed as actual state of the art in production components. Further discussions with these suppliers indicated that while these materials had demonstrated these capabilities in a laboratory environment, they needed further manufacturing development to be reduced to practice. While these promoted capabilities were not used to establish the baselines, they were useful in informing the sensitivity analyses.

Baseline Cost and Energy Metrics

Baseline cost and energy metrics for IACMI were finalized in March 2017. The procedure used to establish the baseline values for these metrics was as follows:

1. Establish the state-of-the-art as of June 2015 (launch date of IACMI) in carbon fiber polymer matrix composite materials, part complexity, performance requirements, and manufacturing processes for automobile, wind turbine blade, and compressed gas storage applications.
2. Calculate the cost metric in terms of $/kg of part weight for representative components and manufacturing methods as of June 2015.
3. Calculate the embodied energy metric in terms of MJ/kg of part weight for the components and manufacturing processes selected for estimating the cost metric.
4. Perform sensitivity studies to assess the dependence of these metrics on several variables such as manufacturing and process waste.
5. With consensus of IACMI members lock in the cost and energy metrics as baseline values for progress tracking.

Details of the part dimensions, processes, data, sources, assumptions made, and the actual calculated metric values are available on the IACMI website in the complete report at https://iacmi.org/baseline-cost-energy. A summary of the parts, processes and tools used to calculate the baseline metrics is shown in Table 1. As shown in the table, conventionally used single manufacturing processes were considered for wind blades (vacuum assisted resin transfer molding) and for compressed gas storage tanks (filament winding followed by cure). For automobile parts, on the other hand, three different processes were considered since part complexity and performance requirements drive the materials combination and process selection. In addition, a fiberglass injection overmolding case was considered for comparison with costs of similarly molded carbon fiber composite parts.

Table 1. Component description, process type and tools used for baseline cost and energy metrics

Technology Area	Component Description	Baseline Manufacturing Process	Cost Metric Calculation Method	Embodied Energy Metric Calculation Method
Wind Turbine Blade	Carbon Fiber/epoxy spar cap for a 61.5 m long blade	Vacuum Assisted Resin Transfer Molding	NREL Structural Model and ORNL cost model	FRPC Energy Estimator
Automobile	Floorpan, 1500 mm by 1200 mm, 2mm thick	High Pressure Resin Transfer Molding	ORNL Cost Model	FRPC Energy Estimator
	Door Inner, 915 mm by 1200 mm by 2.5 mm thick	Injection Overmolding - carbon fiber	ORNL Cost Model	FRPC Energy Estimator
	Door Inner, 915 mm by 1200 mm by 2.5 mm thick	Injection Overmolding - Glass fiber	ORNL Cost Model	FRPC Energy Estimator
	Hood Inner, 1015 mm by 1525 mm by 1,5 mm thick	Prepreg Compression Molding	ORNL Cost Model	FRPC Energy Estimator
Compressed Gas Storage Vessel	Filament Wound H2, Filament wound CNG (64L); Filament Wound CNG (538	Filament winding	Strategic Analysis Activity based cost model	FRPC Energy Estimator

Baseline Cost Metrics

Development of the baseline cost metrics were done by IACMI in conjunction with specialists from Oak Ridge National Laboratory (ORNL). The resulting cost metrics are summarized in Table 2. For wind turbine blades, based on the carbon fiber spar caps, the baseline cost metric was calculated to be $15.58 per kilogram of part weight. For compressed gas storage three different commonly anticipated cases were analyzed and the costs ranged from $34 to $66 per kilogram of the cylindrical storage tank weight with the highest cost corresponding to smaller storage volume. In the case of automobile parts, the size, complexity and process variations resulted in a wide cost range from $25 to $86 per kilogram of part weight with the lowest number corresponding to the fiberglass injection overmolded part.

Table 2. Cost Metrics Summary

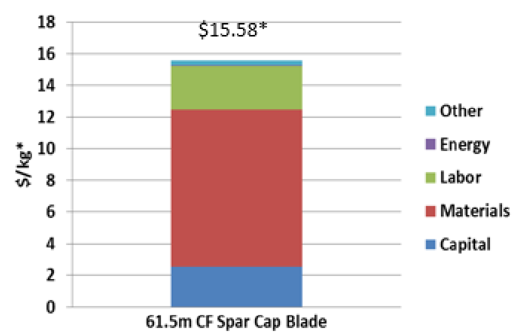
Cost Metrics

	Manufacturing Process	Non-Recurring	Recurring				Total Cost	Scale, Units	Unit Cost $/kg composite
		Capital	Material	Labor	Energy	Other			
Wind	Vacuum Assisted Resin Transfer Molding[a]	$31K	$121K	$33K	$1K	$4K	$190K	930	$15.58
Auto	HPRTM (Floorpan)	$20	$227	$22	$4	$71	$344	100K	$53.84
	Injection Overmolding (Door Inner) – Carbon Fiber	$11	$65	$10	$0.2	$22	$108	100K	$55.59
	Injection Overmolding (Door Inner) -- Glass Fiber	$11	$22	$10	$0.2	$14	$57	100K	$25.45
	Compression Molding (Hood Inner)	$12	$74	$25	$2	$35	$148	100K	$85.96
Pressure Vessel[b]	Filament Wound, H2 Fil. Wound, CNG (64L) Fil. Wound, CNG (538L)	$99 $26 $110	$2293 $379 $3163	$72 $46 $180	$6 $2 $5	$1210 $615 $1052	$3680 $1068 $4510	130K 500K 100K	$27.42 $27.79 $25.43

[a] ORNL 61.5m 12.2 tonne Spar Cap Carbon Fiber Blade Competitiveness Analysis Cost Model (2015)
[b] 70 MPa Type IV H_2 Pressure Vessel and 3600psi CNG storage by Strategic Analysis, Inc. (Cassidy Houchins)

The material costs, in particular carbon fiber costs, are a dominant contributor to the cost per kilogram of part weight in all cases as illustrated in Figures 1, and 2 below for wind blade spar caps, and cylindrical compressed gas storage tanks, respectively. As seen in Figure 1 for wind turbine blades, material costs are 64 percent of the total spar cap cost of which carbon fiber costs contribute slightly more than one-third.

- Material contributes to ~64% of total blade cost, of which carbon fiber share is 35% -- low cost carbon fiber availability is critical for its widespread use
- Capital and Labor have similar cost share, i.e., ~16% each -- automated fiber placement and shorter cycle time would improve its economic viability
- Other remaining cost components have a less than 5% of total cost share, of which manufacturing energy is the least significant



*Based on total blade weight; Other cost category includes capital maintenance cost

Figure 1. Breakdown of wind turbine blade spar cap cost per kilogram of part weight.

Similarly, for CFRP storage tanks, Figure 2 shows that the material cost contribution to the total tank cost is 62 percent, a majority of which (~87%) is carbon fiber cost.

- Material contributes to 62% of total tank cost, of which carbon fiber share is 86.5% -- low cost carbon fiber is one of the major options considered for its economic viability
- Balance-of-Plant (BOP) is another major contributor to tank cost, ~30%
- Other remaining cost components have a less than 5% of total cost share, energy is among one

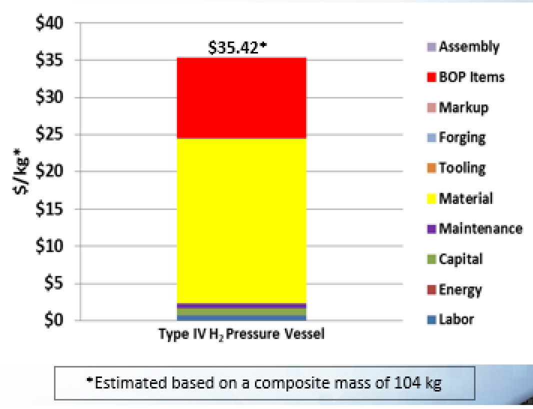


Figure 2. Breakdown of compressed gas storage tank cost per kilogram of part weight.

The impact of carbon fiber costs and tank mass on the costs per kilogram of composite storage tanks was assessed by means of a sensitivity study. The results of this sensitivity analysis are summarized in Figure 3, where it can be seen that fiber price reduction alone within the currently projected practical minimum, can reduce tank costs between 32 and 38 percent, depending on the tank size. With concurrent mass reduction, the costs per kilogram drop by as much as 49 to 57 percent, depending on tank size.

- Sensitivity analyses were performed to evaluate which factors could drive down overall tank costs.
- Fiber price and mass reduction clearly have the most impact.
- Mass reduction can be achieved by:
  - Lowering factor of safety from 2.25
  - Improving fiber translation
  - Reducing COV in process
- 50% reduction in capital costs yields 2% reduction in tank cost
- 50% reduction in resin cost yields 6% reduction in tank cost

64L

Fiber Price	Mass Reduction			
	0%	10%	25%	33%
$28.66/kg	-	-8%	-21%	-28%
$21.50/kg (-25%)	-16%	-23%	-33%	-39%
$14.33/kg (-50%)	-32%	-38%	-45%	-49%

538L

Fiber Price	Mass Reduction			
	0%	10%	25%	33%
$28.66/kg	-	-10%	-24%	-32%
$21.50/kg (-25%)	-19%	-27%	-38%	-52%
$14.33/kg (-50%)	-38%	-43%	-52%	-57%

Source: Strategic Analysis, Inc.

Figure 3. Tank cost metric sensitivity to carbon fiber cost and tank total mass reduction.

The dominance of carbon fiber prepreg costs in automobile CFRP part costs is illustrated in Figure 4 by way of the bar designated “Baseline” where material costs constitute nearly 50 percent of the total part cost per kilogram for the prepreg compression molding process. The figure also shows the sensitivity of the cost metric to fabrication cycle time. Lower cycle times, as intuitively expected, reduce the cost per kilogram but the material costs are a higher percentage of the cost metric. Overall, the cost metric is sensitive to the process cycle time increasing to $ 100 per kilogram for a 17-minute cycle time.

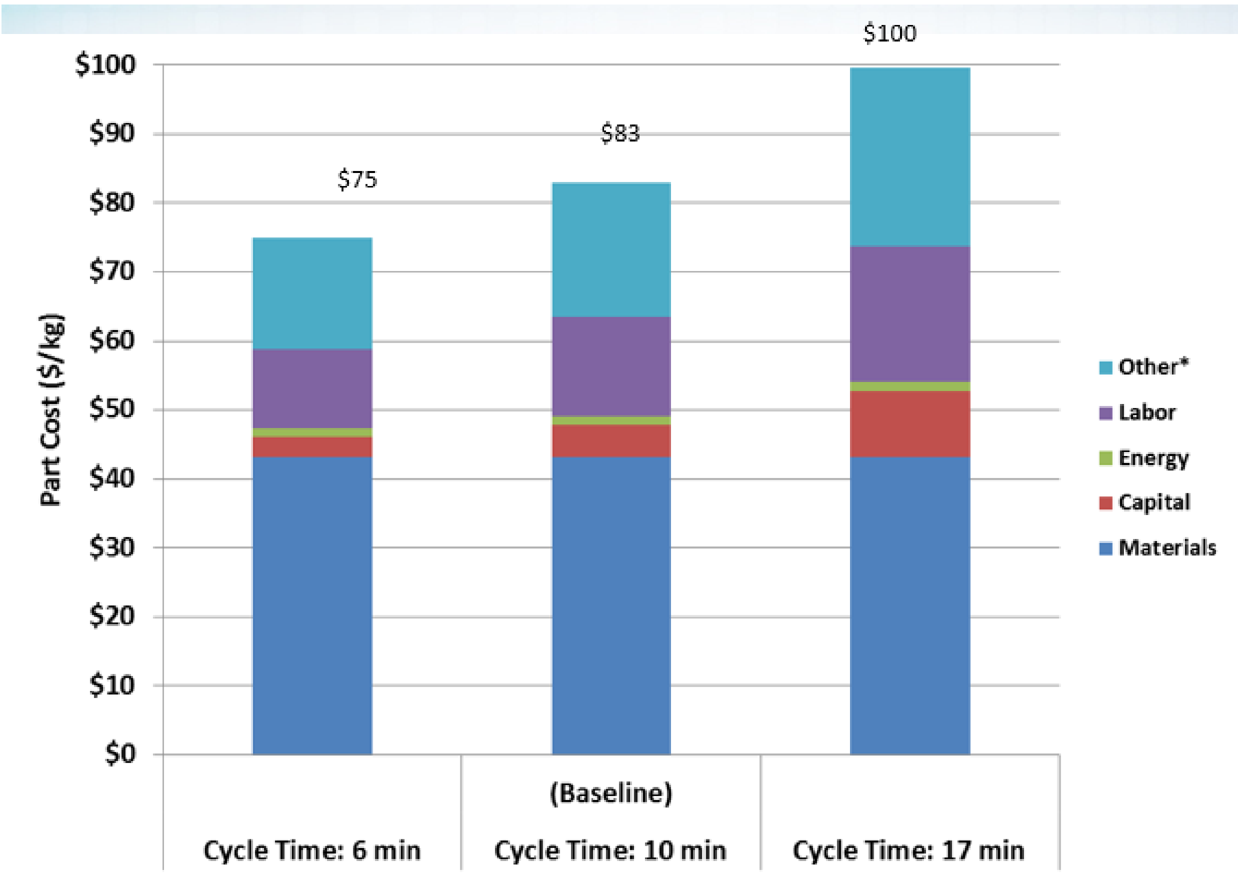


Figure 4. Cost per kilogram of automobile part weight sensitivity to fabrication process cycle time. Prepreg compression molding process assumed.

Cycle time sensitivity calculations were also carried out for the other three processes used in defining the automobile cost metric. These sensitivities, along with the cost metric dependence on the part size as measured by its weight are shown in Figure 5. The cost metric for all four processes increases with cycle time for all part sizes considered. Detailed breakdown of the costs by materials, labor etc. for the prepreg compression molding (PCM) process was shown earlier in Figure 4. The cost metric, as can be seen in Figure 5 was most sensitive to cycle time when the part weight was 1.5 kg. The slope of the cost metric versus cycle time plot diminishes substantially as the part weight increases to 10 kg, thus indicating that larger the consolidated part size lower the influence of cycle time on the cost metric. The cycle times considered were process specific with the lower values achievable by advancing the state-of -the-art for the respective processes.

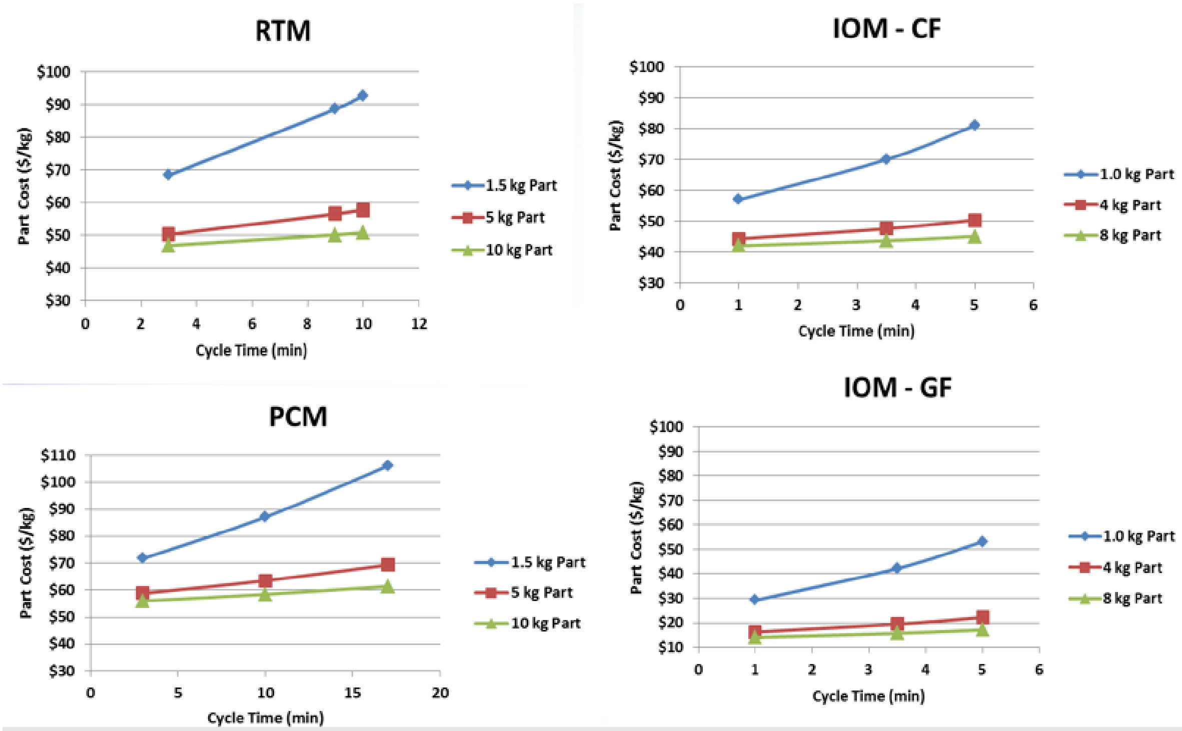


Figure 5. Cost metric sensitivity to fabrication cycle time and part size for all processes considered in defining the metric for automobile parts.

A similar set of calculations for the four processes were carried out to determine the sensitivity of the cost metric to materials costs since they are a dominant contributor to the metric. These results are shown plotted in Figure 6. As expected, the metric varies linearly with the material costs in all cases. However, for larger part sizes, e.g., 5 kg and 10 kg, the cost metric is reduced for the same material cost even if the sensitivity to material cost for each weight grade remains the same as for the baseline 1.5 kg part. Material cost sensitivity of the cost metric is greater for the prepreg compression molding and the high pressure resin transfer molding processes than the injection molding processes.

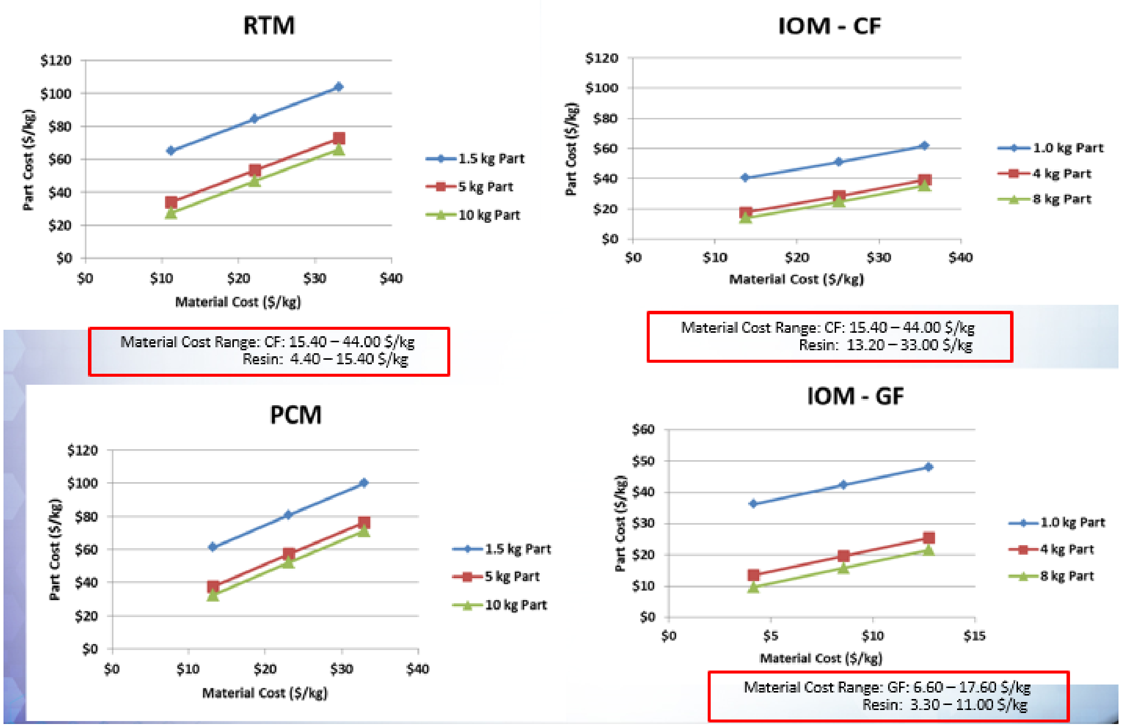


Figure 6. Cost metric sensitivity to material costs and part size for all processes considered in defining the metric for automobile parts.

A concern in the productionizing of CFRP fabrication processes for automobile parts has been the feasibility and cost of producing large quantities of parts. Results of a sensitivity study that examined the dependence of the cost metric on the quantities of parts produced annually is shown in Figure 7.

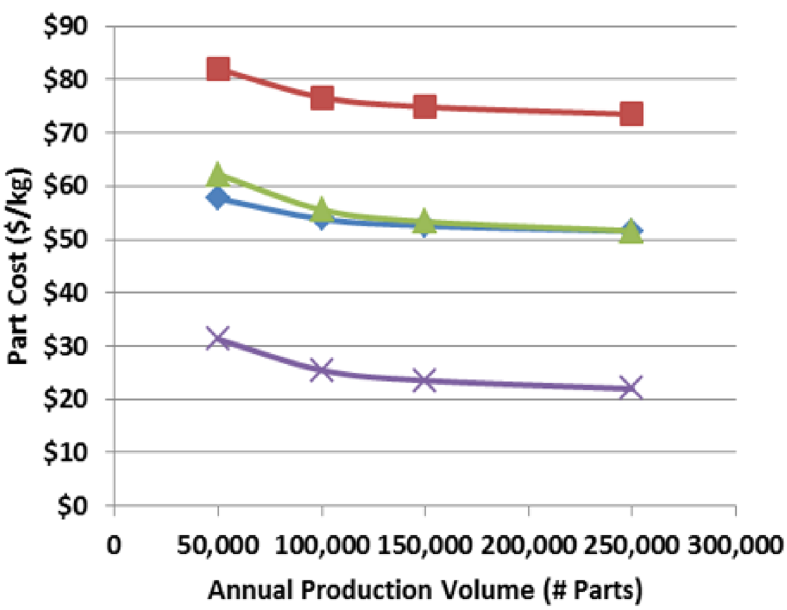
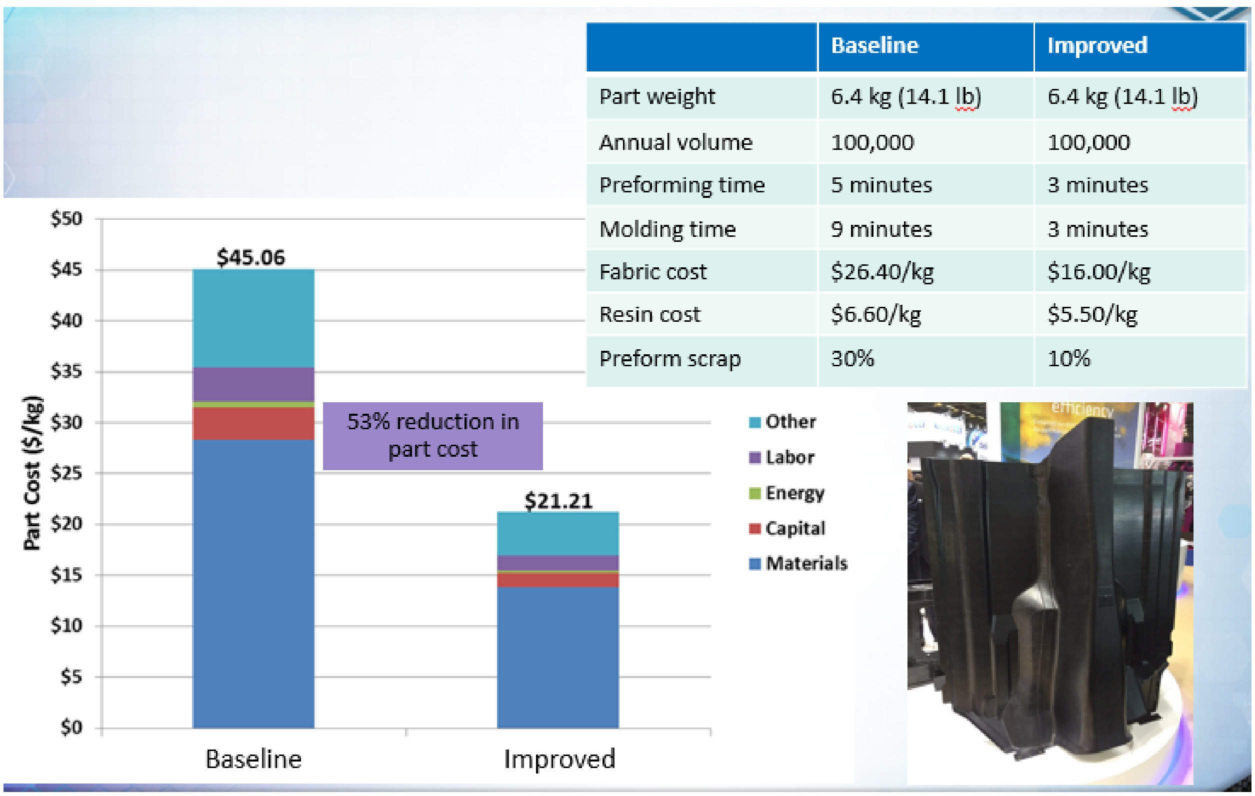


Figure 7. Cost metric dependence on annual production volume of automobile parts for the four processes considered in defining the metric.

As evident from the figure, the cost metric decreases as much as 17 percent for CFRP automobile parts when the annual production volume increases from 50,000 to 150,000 parts. The sensitivity curves flatten out as the annual production volume increases to 250,000 parts. The cost metric reduction for fiberglass injection overmolded parts with comparable annual production volumes is higher at approximately 25 percent.

Another factor that influences the cost metric is the scrap inherent in the processes considered. In the absence of reliable scrap factor data, a case study using the High Pressure Resin Transfer Molded (HPRTM) floor pan was conducted with assumed scrap rates for current and an advanced more efficient process. The case study also included current and projected material costs, and cycle times after 5 years of IACMI sponsored advancements. The results are summarized in Figure 8 where reducing the preforming cycle time from 5 minutes to 3 minutes, the molding cycle time from 9 minutes to 3 minutes, carbon fiber costs from $26.40 per kg to $16 per kg, resin costs from $6.60 per kg to $5.50 per kg, and the scrap factor from 30 percent to 10 percent, all combined to reduce the cost metric by 53 percent. The synergistic effect of these multiple impacts is expected to make CFRP more attractive to cost sensitive markets like automotive.



	Baseline	Improved
Part weight	6.4 kg (14.1 lb)	6.4 kg (14.1 lb)
Annual volume	100,000	100,000
Preforming time	5 minutes	3 minutes
Molding time	9 minutes	3 minutes
Fabric cost	$26.40/kg	$16.00/kg
Resin cost	$6.60/kg	$5.50/kg
Preform scrap	30%	10%

Figure 8. Case Study Illustrating the use of cost metrics to drive technology developments for economically feasible production of CFRP automobile parts.

Baseline Embodied Energy Metrics

Embodied energy of a finished part is the energy consumed by all of the processes associated with the production of that part ranging from the mining and processing of natural resources to manufacturing, transport and product delivery. For metrics related calculation of embodied energies in this report, the

Fiber Reinforced Polymer Composite (FRPC) Energy Estimator[1] tool developed by Sujit Das and Kristina Armstrong of ORNL was used. A full user guide and detailed methodology of how the estimator works is available online at http://www.energytoolestimator.com/

The FRPC Energy Estimator contains a database of the embedded energies for various fiber and matrix materials from referenced Life Cycle Analysis (LCA) literature, and the energies intrinsic to each major step in composites manufacturing processes representative of current practice. The embodied energy estimating process underlying the FRPC Energy Estimator is schematically illustrated in Figure 9. As shown in the figure, the individual embodied energies of the matrix, fiber and the manufacturing process used are summed to calculate the total embodied energy of a finished part. The variables in estimating these individual energies are, for example, the carbon fiber precursor type, its production process, i.e., number of heat treatment and mechanical stretching steps, the source and production method of matrix materials, the fiber volume of the finished part, distinct steps in the manufacturing process, and the type of finishing operations.

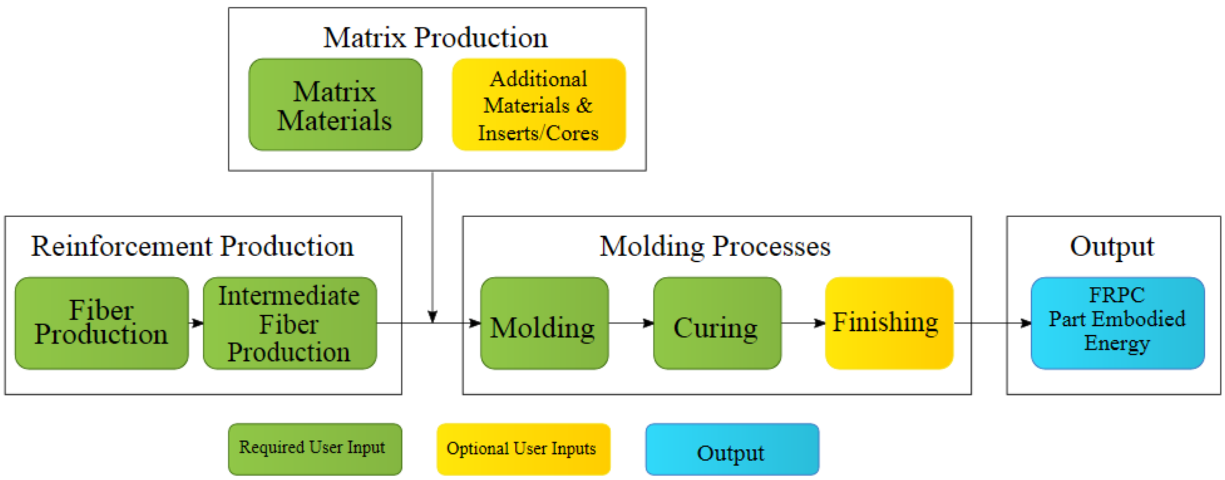


Figure 9. Fiber Reinforced Polymer Composite (FRPC) Energy Estimator calculation methodology for embodied energy of finished composite part.

The baseline embodied energy metrics corresponding to the parts and processes considered in the calculation of cost metrics of Table 2 are shown in Table 3. Due to the high energy intensity of manufacture, the embodied energy of carbon fiber production processes is the dominant contributor to the total embodied energy of a CFRP part and more so than in the cost metrics.

[1] Armstrong, K. and Das. S. (2017). "Fiber Reinforced Polymer Composite Tool: User Manual," Oak Ridge National Laboratory, Oak Ridge, TN. May 2017. Available online at: http://www.energytoolestimator.com/

Table 3. Embodied Energy Metrics Summary

Energy Intensity Metrics

(Numbered references see pages 41-42)

	Manufacturing Process	Fiber Volume Fraction	Embodied Energy Intensity (MJ/kg)				
			Fiber	Int. Fiber Form	Resin	Molding and Curing	Total
Wind[c]	Vacuum Assisted Resin Transfer Molding[11]	74%	118[g] [(1,2)]	5[(3)]	4[(10)]	4[(12)]	131
Auto	HPRTM (Floorpan)	50%	1130[(1)]	34[(3)]	46[(10)]	63[(14)]	1273
	Injection Overmolding (Door Inner)[d] – Carbon Fiber	24%	538[(1)]	8[(5)]	52[(9)]	12[(15,16)]	610
	Injection Overmolding (Door Inner)[e] – Glass Fiber	23%	26[g] [(1)]	8[(5)]	48[(9)]	12[(15,16)]	94
	Compression Molding (Hood Inner)	50%	1183[(1)]	127[(4)]	70[(10)]	29[(13)]	1409
Pressure Vessel[f]	Filament Winding	68%	739[(1)]	NA	34[(10)]	4[(11)]	777

[c] ORNL 61.5m 12.2 tonne Spar Cap Carbon Fiber Blade Competitiveness Analysis Cost Model (2015)
[d] 30wt% fiber content in injection compound; [e] 35wt% fiber content in injection compound
[f] Based on 104 kg Composite; [g] Wind is hybrid of carbon and glass, overmolding glass is glass fiber only

The initial baseline cost and embodied energy metrics of Tables 2 and 3 are intended to serve as "starting points" for comparing technology, material and equipment cost improvements and their effect on total part cost and energy consumption. These baseline metric values are representative of current practice and market conditions.

Turbine blade costs represent a significant capital expense in the wind energy industry. Reduction in manufacturing time and carbon fiber costs are expected to translate to lowering blade costs to the point where domestic manufacturer's market penetration is increased.

In vehicles, material costs and cycle times (which affect capital, tooling and labor costs) are major levers in reducing part costs and, therefore, improving the value proposition for increased incorporation into future platforms. Larger components are also more economical, favoring part integration or multi-cavity molding of small parts. Initial calculations have assumed zero to minimal recovery or reprocessing of material scrap. This practice is expected to change and have a positive effect on part costs in the future. For compressed gas storage, the cost of high strength carbon fiber is the most significant element. Reductions in design safety factors or carbon fiber cost will be required to significantly impact pressure vessel costs.

For all applications, embodied energy is mainly influenced by the manufacture of carbon fiber. Reductions in the energy intensity of carbon fiber manufacture, along with reductions in material scrap rates, are needed to achieve IACMI goals in this area.

IACMI will use these baseline calculations to measure the impact of activities within IACMI projects as well as industry advances conducted external to IACMI to assess progress towards cost and embodied energy goals. At least annually, IACMI will publish progress toward these objectives based on then-current-state-of-the art. Additionally, the methodology used to derive the baseline metric values will be applied, as appropriate, to additional applications and relevant advanced composite markets.

Section 3: Impact of Advances in Rapid Fabric Formation (RFF) and Pultruded Wind Turbine Blade Spar Cap

This section describes the impact of two recently completed IACMI sponsored technology projects on the baseline metrics described in Section 2.

Example Component Selection

In the first project, titled "Thermoplastic Composites Parts Manufacturing Enabling High Volumes, Low Cost, Reduced Weight with Design Flexibility", a highly drapable, easily recyclable, thermoplastic coated, near net shape carbon fiber fabric was developed. The thermoplastic coated tow (CT) fabric was manufactured using a rapid fabric formation (RFF) process developed for textile manufacturing. The DuPont, Fibrtec, and Purdue University team that accomplished the development of this low scrap rate carbon fiber product form has selected an automobile control arm shown in Figure 10 to be built in a follow-on phase of the project as a demonstrator of the benefits of this technology. To evaluate the potential impact of this technology on the baseline metrics, cost and embodied energy per unit weight were calculated for the control arm using the same methodology described in Section 2 that was used to calculate the baseline metric values. The results are described in the following sub-sections.

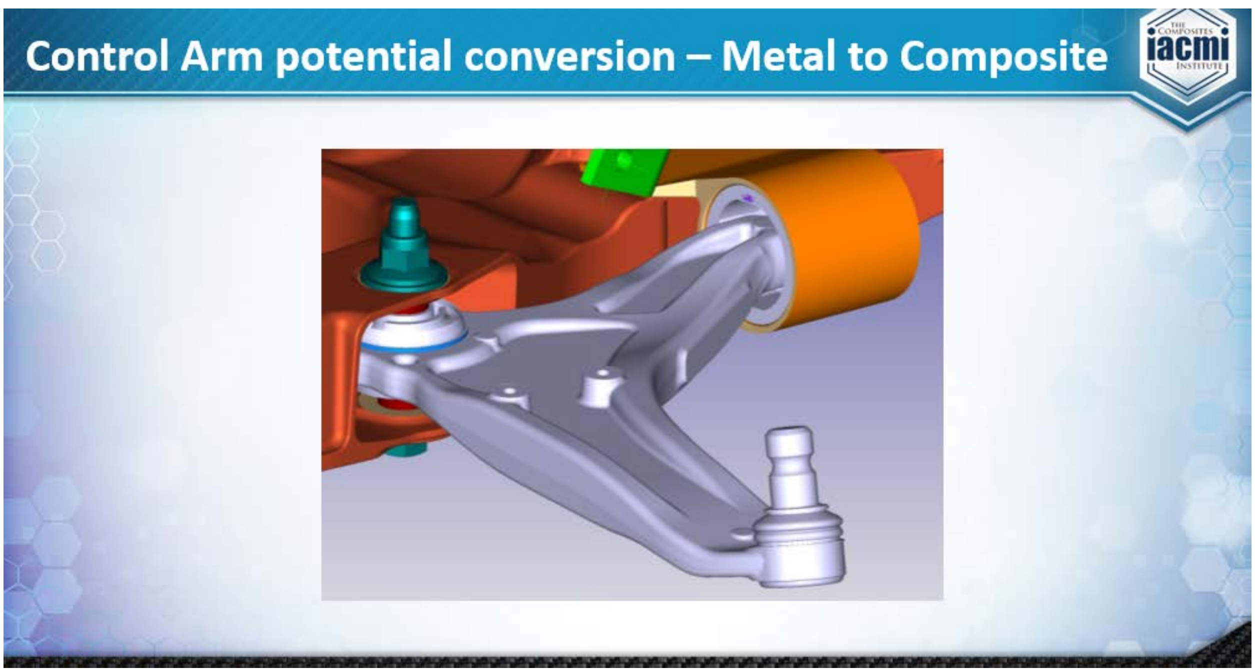


Figure 10. Automobile control arm demonstrator for the thermoplastic Rapid Fabric Formation technology

The second completed IACMI project was a 9-meter wind turbine blade technology demonstrator incorporating a novel reactive infusion resin that results in a thermoplastic matric for the skins and shear web, coupled with a pultrusion process for a carbon fiber polyurethane matrix wind blade spar cap using a textile PAN-based carbon fiber developed at ORNL. This pultruded carbon fiber/polyurethane matrix spar cap was analytically scaled up to the 61.5 meter blade, shown in Figure 11, used for establishing the baseline cost and embodied energy metrics as described in Section 2. The impact on the baseline wind blade metrics of this scaled up carbon fiber/polyurethane matrix spar cap was estimated by calculating its cost and embodied energy per unit weight using the same methodology that was used to calculate the baseline metric values as described in Section 2. These results are also described in the following sub-sections.

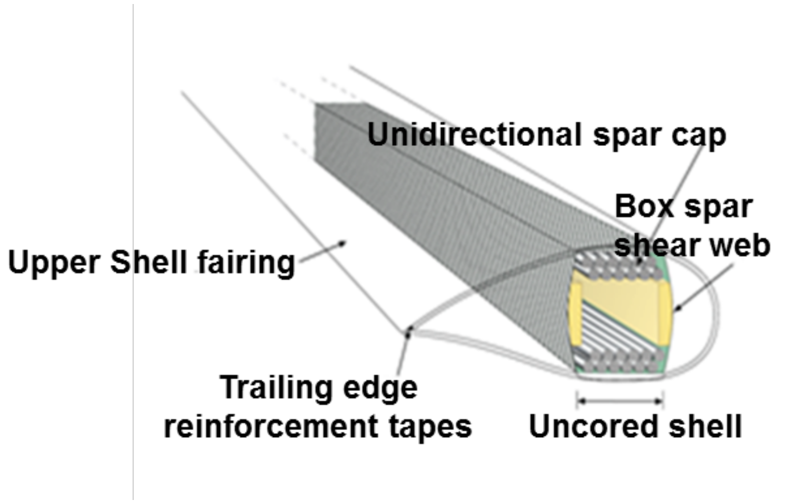


Figure 11. Schematic of carbon fiber spar cap in a 61.5 meter long wind turbine blade.

Impact of RFF Technology on Baseline Metrics

Evaluating the impact of RFF technology on baseline metrics required baseline thermoplastic material and consolidation process definition and several assumptions to keep a level playing field for the comparison. A woven continuous carbon fiber and polyamide matrix in organosheet[2] material and a compression molding process representative of the current state-of-the-art were selected as the baseline for this impact assessment study.

The control arm was assumed to weigh 5 kg in its final carbon fiber composite form whether it was built using organosheets or the thermoplastic coated RFF product form. For comparison, if the current control arm were to be aluminum, its weight would be scaled up by the ratio of material densities to 8.5 kg, as a first approximation. Key differentiators between the organosheet and the RFF product form built control arm were in the yields in the upstream processes such as fabric weaving, resin casting for organosheets, and tow coating for RFF, along with the differences in scrap rates. Figure 12 illustrates the various upstream steps in fabric formation and impregnation for the two product forms and the associated yields which were obtained from DuPont. The steps after preform fabrication shown in Figure 12 of preheating the preform, compression molding and trimming the flash for a finished part were identical for both product forms.

[2] An organosheet is a continuous carbon fiber in a dry thermoplastic matrix prepreg similar to a tacky thermoset prepreg. As opposed to rolls of continuous thermoset prepreg, organosheets are supplied in standard sizes, e.g. 400 mm by 600 mm, or sizes customized to a production application.

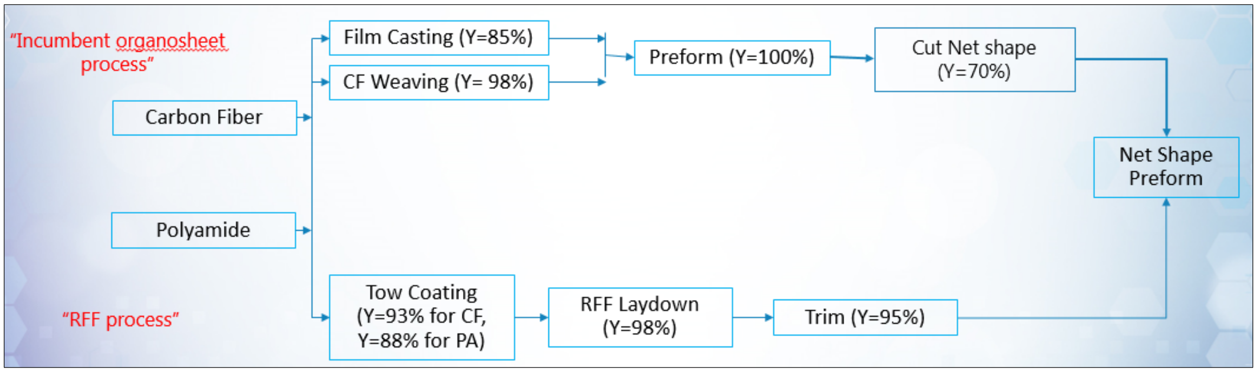


Figure 12. Process steps, yield and scrap rate assumptions to obtain the net shape preform starting with carbon fiber/thermoplastic organosheet and RFF materials. Downstream processes of preform preheating, compression molding and finish trimming are assumed to be identical for both starting materials.

The volume of parts produced annually plays a significant role in estimating the cost per unit weight of the part. In this instance, based on DuPont's business projections, it was assumed that 2 K metric tons (2,000,000 kg) of preform would be manufactured annually resulting in 400,000 control arms for 200,000 vehicles. As sensitivity studies in the baseline metrics calculations have shown, the cost per unit part weight versus annual production volume curves are relatively flat from approximately 100,000 units to 200,000 units. For volumes as low as 50,000 units the cost metric increase could be as much as 20 percent depending on part size. Thus, the cost metrics calculated for the control arm with the assumed annual production volumes are applicable to production volumes as low as 100,000 units.

Control Arm Cost Comparison – RFF vs. Organosheet

A grassroots cost model was used to calculate the control arm costs for the manufacturing processes corresponding to the organosheet and the RFF materials. The data used and the accompanying assumptions for these cost calculations are summarized in Appendix C.

Table 2 shows the total costs per kilogram of part weight and their breakdown into constituents such as capital, labor and materials for the organosheet and the RFF control arms. In both cases, the total cost per unit weight is dominated by material costs. The "Other" column represents General and Administrative Overhead and is a fixed percentage applied to the subtotal of capital, materials, labor and energy costs. In both cases the molding cycle time is assumed to be 2 minutes.

Table 4. Cost Per kilogram of part weight for the organosheet and RFF control arms

	Capital	Materials	Labor	Energy	Other	Total
Baseline	$0.17	$44.18	$1.47	$0.19	$9.45	$55.47
RFF	$0.20	$24.61	$1.56	$0.17	$5.54	$32.08

A spot check with the baseline metrics of Section 2 shows that the organosheet costs are of the same pedigree as the baseline metrics. This is illustrated in Figure 13, taken from Section 2 Figure 5 corresponding to the prepreg compression molding process, where if the 5 kg part weight curve is extrapolated back to a 2min cycle time as in the present organosheet case, the cost per unit weight is approximately $ 55/kg which is nearly identical to the organosheet control arm cost shown in Table 2. A comparison of the two cost metrics in Table 2 indicates that the RFF process cost savings are approximately 42%.

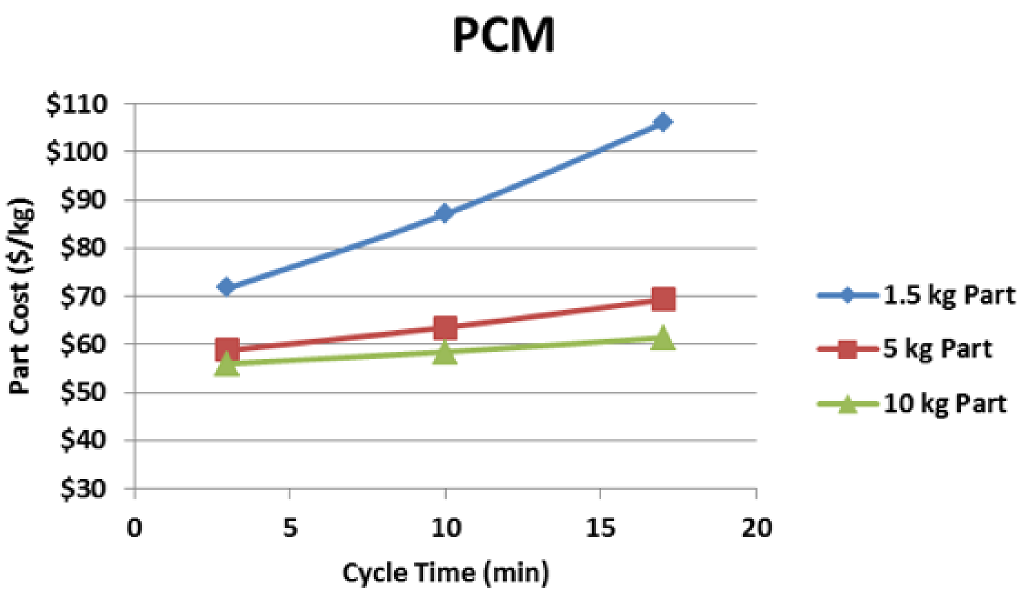


Figure 13. Cost/Kg sensitivity to part weight and cycle time

Figure 14 shows the total costs and their constituents in a bar chart form for the two types of control arms. The material cost bar for the RFF material is lower as a combination of the various yields, almost no scrap and the lower cost of towpreg material at $22.04/kg as compared to the organosheet cost of $29.75/kg., Both material costs were provided by DuPont, which supplies both types of materials. The slightly higher labor costs for the RFF material is the additional labor required to tack or glue the fiber assemblage at strategic points. The "other" costs for the RFF control arm are automatically lower since they are a fixed percentage of the subtotal of all capital, material, labor and energy costs.

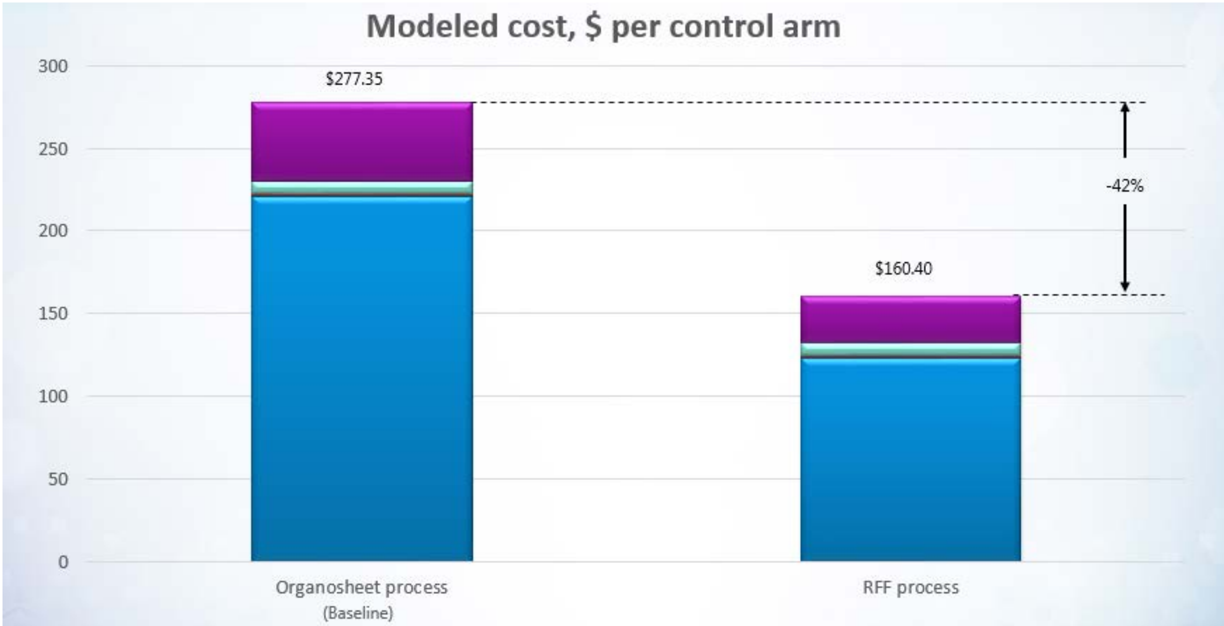


Figure 14. Control arm cost comparisons.

These cost data show a 42 % improvement in part cost; but, to determine with reasonable confidence whether this part can "buy" its way on to an actual vehicle would require additional data assuming the currently used material is aluminum. In particular, a more accurate representative metal part weight needs to be obtained from the Original Equipment Manufacturer (OEM) and the costs estimated using this methodology for the aluminum and composite parts. Further, the metal part costs need to be increased by a $/kg of weight saved payoff to the OEM and additional penalty costs for corrosion susceptibility and the increased durability of the composite part.

Thermoplastics would be the matrix of choice as opposed to thermosets for this application, since they offer shorter cycle times with a stamping process and no material cost or environmental exposure penalties. The added advantage of an easier path to recycling the component at end of life would also be a consideration in favor of thermoplastics.

Control Arm Embodied Energy – RFF vs. Organosheet

The FRCP energy estimator tool described in Section 2 was used to calculate the embodied energy metrics for the control arm using the materials and processes summarized in Figure 12. For the purpose of these calculations, it was assumed that the finished control arm had 64 percent by weight of carbon fiber with the balance being the thermoplastic matrix. The results of the calculations are summarized in Table 5.

Table 5. Embodied energy calculations and resulting metrics for organosheet and RFF materials

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	**Organosheet Process**			Wf, Kg	EE Prehea	EE CM	EE Trim	Wf w. Scra	R/Cast Eff	R/Weave	EE Cast	EE Weav	EE Gerber	EE CF	EE PA 66	
2				5				7.14	0.85	0.98	@24	@36	@ 17.2 KW for 2 min	@1166	@ 140.75	
3			RC 36%	1.8				2.57	3.02							
4			FC 64%	3.2				4.57		4.66						
5	**1249.9**	**6249.64**			6	138.5	0.491				72.37	167.93	0.896	5439.07	424.39	
6																
7																
8																
9	**RFF Process**							Wf/RFF Tr	R/Laydow	S/Tow Co	S/Tow Co	EE Pultr	EE Dry we	EE Gerber	EE CF	EE PA66
10				5				5.26	5.37			@9.7	@36/Kg			
11			RC 36%	1.8				1.89	1.93	2.20		5.9				
12			FC 64%	3.2				3.37	3.44		3.70					
13	**1004.1**	**5020.63**			6	138.5	0.491					57.23	193.3	1.22	4314.20	309.65

The table requires explanation, because it starts with the finished part weight of 5 kg in cells D2 and D10 for the organosheet and RFF materials, respectively, and backtracks to the starting composite weight after adjusting for all the yield and scrap rates to calculate the embodied energy. Cells D3, D4, D11, and D12 breakdown the part weight into fiber and resin weights based on the assumed weight fractions. The populated cells in Columns D, E and F are the calculated embodied energies for the preform preheat, compression molding and finish trimming processes. As can be seen in Table 5, the numbers are identical for both starting materials. Column H shows the weight adjusted for scrap (30 %) for the organosheet case and preform trim (5% loss) for the RFF material. Cells I3 and J4 show the matrix and fiber weights adjusted for film casting yield (85%) and yield in fiber weaving (98%) for the organosheet process. Similarly, for the RFF preform, Cell I10 adjusts the composite weight for laydown yield (98%), and Cells J11 and K12 represent adjustments for the carbon fiber and matrix yields (93% and 88%, respectively).

Having calculated the starting weights for the carbon fiber and matrix materials, the next few columns show the embodied energy calculation results. For the organosheet material: Cell K5 shows the embodied energy in resin casting, Cell L5 shows the embodied energy for the carbon fiber fabric weaving process, Cell M5 shows the embodied energy for the Gerber cutting process to get the preform to net shape, Cells N5 and O5 show the embodied energies in carbon fiber production (@ 1166MJ/kg) and thermoplastic matrix production (@ 140.75 MJ/kg). The total embodied energy in fabricating and converting the organosheet prepreg to the finished control arm is shown in Cell B5 and the corresponding metric for the process is shown in Cell A5 as 1249.9 MJ/kg.

For the RFF material: Cell L15 shows the embodied energy of the tow coating process by pultrusion, Cell M5 contains the embodied energy of the RFF dry weaving process, Cell N5 shows the embodied energy of Gerber cutting the preform to net shape, Cells N15 and O15 show the embodied energies in carbon fiber production (@ 1166MJ/kg) and thermoplastic matrix production (@ 140.75 MJ/kg). The total embodied energy in fabricating and converting the RFF prepreg to the finished control arm is shown in Cell B15 and the corresponding metric for the process is shown in Cell A15 as 1004.1 MJ/kg. This represents a 19.7 % improvement in the energy metric for the RFF based control arm production.

Figure 15 shows the calculated total embodied energy numbers for the organosheet and RFF material control arms along with its breakdown into fiber, resin and processing embodied energy contributions. A close examination of Table 5 shows that the nearly 20 % improvement in the embodied energy metric is primarily due to the 30 % offal scrap inherent in the organosheet process, versus the ability to use a net shape flat pattern for the RFF fabric due to its drapability. Potential recycling of the scrap could reduce the net improvement in the embodied energy metric for the RFF material control arm.

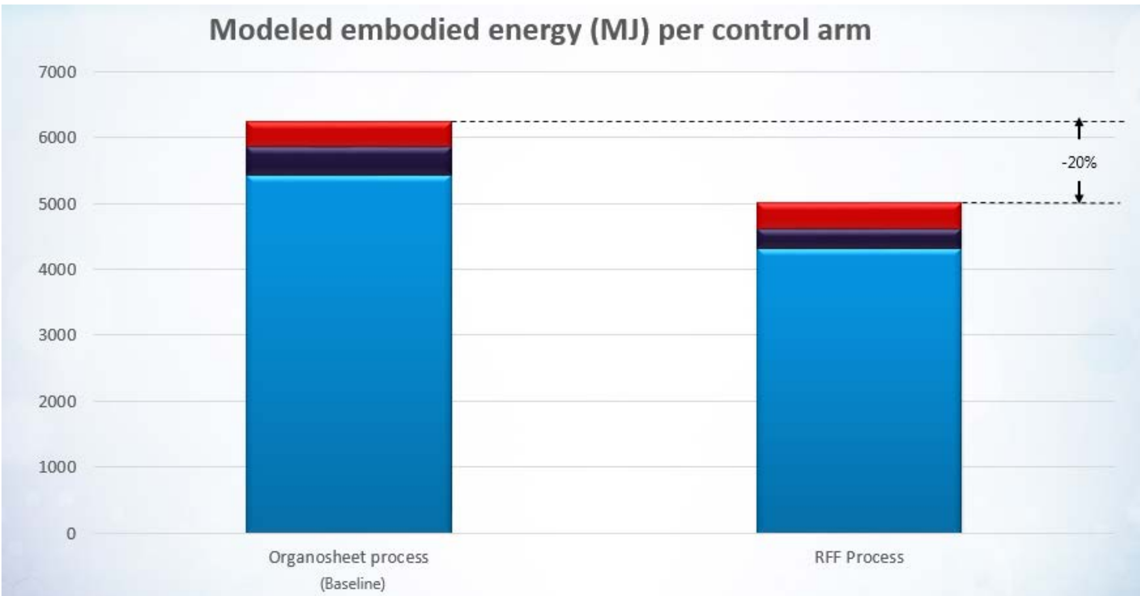


Figure 15. Embodied energy comparison for 5 kg control arm with two different starting product forms.

It is noted that essentially all the embodied energy savings with the RFF process are due to the technology development sponsored by IACMI in the DuPont led project. The savings demonstrate the effectiveness of the RFF process as compared with the conventional prepreg stamping from roll goods process.

Impact of Carbon Fiber/Polyurethane matrix Spar Cap Pultrusion Technology on Baseline Metrics

The embodied energy impact of using a pultruded carbon fiber spar cap in lieu of the traditional VARTM fabricated carbon fiber or glass fiber spar cap was calculated using the previously mentioned FRPC energy estimator tool. Cost calculations for the spar cap utilized a NREL developed cost model also used for the baseline cost metrics calculations. Figure 16 summarizes key aspects of the NREL model and the assumptions used. Additional details of material and process assumptions are shown in Appendix C.

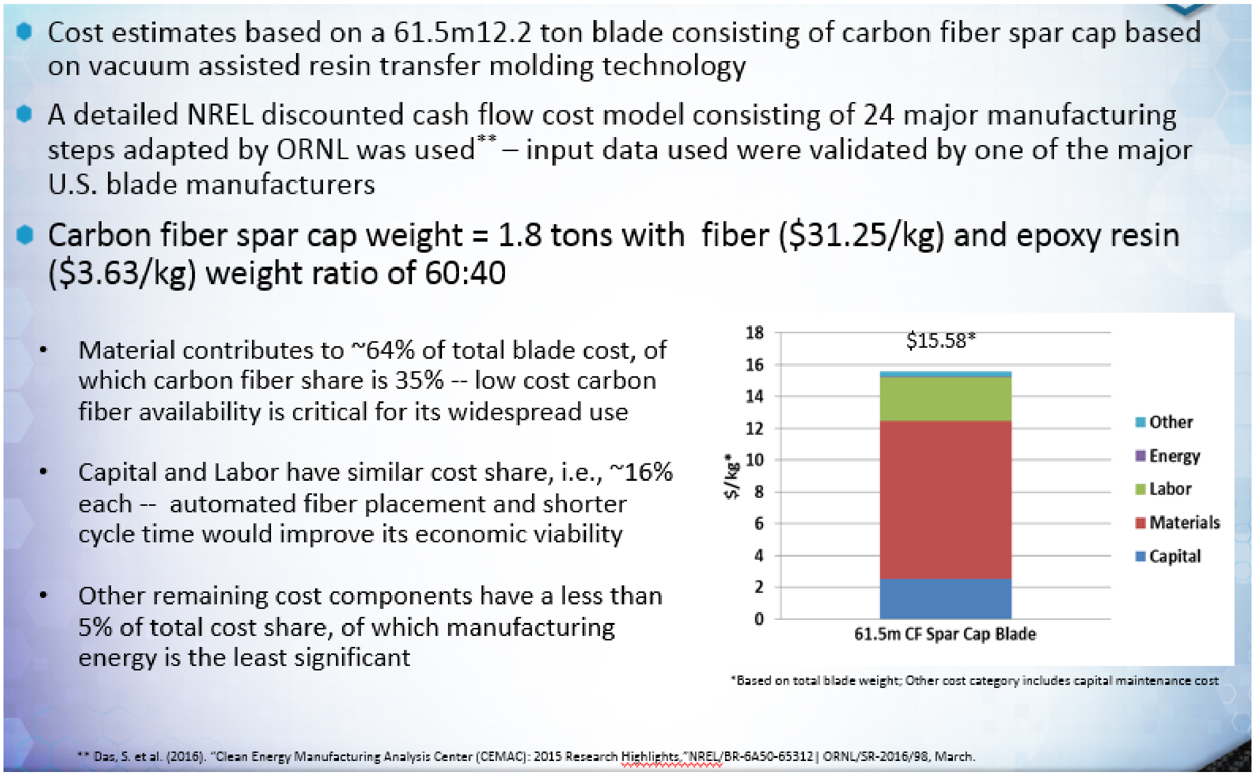


Figure 16. Key NREL cost model features and assumptions for carbon fiber spar cap cost calculations.

Four variations were considered for embodied energy and cost calculations of the spar cap. These were: (i) Fiberglass spar cap fabricated by a VARTM process, (ii) Standard Commercially available carbon fiber spar cap fabricated by VARTM process (baseline material and process), (iii) Low Cost Carbon Fiber (textile PAN-based fiber) spar cap fabricated by a VARTM process, and (iv) Low Cost Carbon Fiber (textile PAN-based fiber) spar cap fabricated using a pultrusion process. The baseline spar cap for the 61.5m blade developed by NREL is a carbon fiber non-crimp fabric infused with epoxy resin. The wind energy market, being very cost-competitive, favors lower cost fiberglass spars where they can be practically employed. For purposes of comparison, an equivalent stiffness fiberglass spar cap, infused with epoxy resin, was also included in the analysis to see how it compares to the lower cost carbon fiber outcomes. The results are discussed in the following sub-sections.

Carbon Fiber Spar Cap Cost Comparisons

The actual calculations and assumptions related to scrap and yields are summarized in the table given in Appendix A. A comparison of the total cost and a breakdown of its contributors for the four spar cap cases enumerated above is shown in Table 6. For this analysis, a slightly lower price ($27.30/kg vs. $31.25/kg) for the baseline carbon fiber fabric was used, to reflect current fiber pricing, so as to not unfairly penalize the baseline case.

Table 6. Components of the total costs of the four spar cap cases

	Capital	Materials	Labor	Energy	Other	Total
Fiberglass NCF/VARTM	$694	$18,293	$5,316	$153	$4,950	$29,406
Commercial CF NCF/VARTM (baseline)	$694	$34,899	$5,316	$40	$8,249	$49,198
LCCF NCF/VARTM	$694	$28,131	$5,316	$40	$6,895	$41,076
LCCF/Pultrusion	$405	$14,670	$1,056	$87	$3,279	$19,497

Material costs represent the dominant driver of overall spar cap cost, in excess of 60% in all cases. The pultruded textile PAN-based carbon fiber has the most attractive material costs as the fiber is used in an as-produced format, eliminating the weaving step required for the other three cases.

Figure 17 shows the relative weights and costs of the four spar cap cases. The significant reduction in weight from 6840 kg for fiberglass epoxy spar cap to the 1800 kg carbon fiber epoxy spar caps was scaled from empirical data from TPI Composites for 48.5m blades that showed a 3.8 to 1 weight ratio between fiberglass and carbon fiber spar caps. All spar caps except the pultruded one used the same epoxy resin. The pultruded spar cap used a polyurethane resin and a process developed by IACMI in the course of fabricating a 9m technology demonstrator blade.

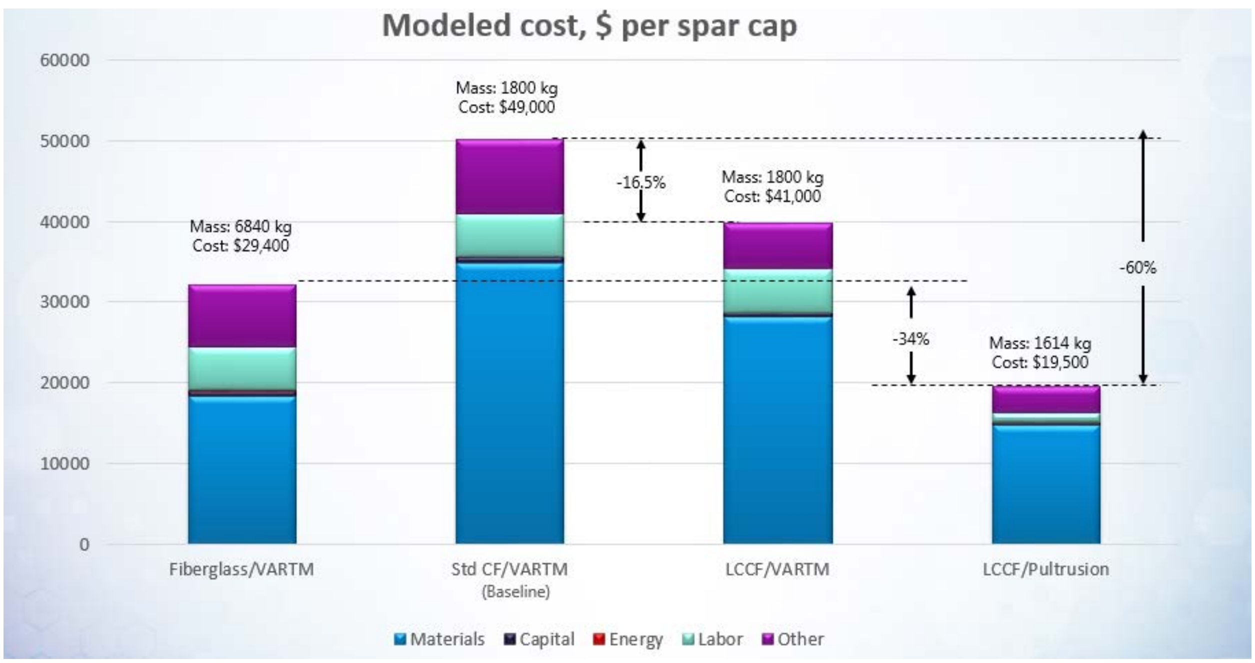


Figure 17. Comparison of the costs for the various spar cap materials and process combinations evaluated.

Consistent with industry practice, the baseline carbon fiber spar caps produced using the VARTM process and conventional carbon fiber are much higher cost than fiberglass spar caps, providing minimal incentive for conversion to carbon unless absolutely necessary for performance. Substituting textile-PAN/low cost carbon fiber for standard fiber in the VARTM process ($21.56/kg vs. $27.30) enables a 16.5% cost reduction for the equivalent mass, but is still 39% higher cost than the much heavier glass fiber spar cap. Using the efficient pultrusion process reduces the weight of the spar cap through reduced resin content, and eliminates the costly weaving step. It also requires significantly less manufacturing labor, although equipment costs are slightly higher than VARTM. The analysis shows a combined cost reduction of 60% versus the baseline VARTM/commercial carbon fiber, and a 34% cost reduction against the fiberglass/VARTM spar cap. During development of the 9-meter blade, IACMI successfully pultruded the textile PAN in a limited quantity, proving this could be done. Due to a limited availability of the material, the low cost textile PAN-based fiber was blended with commercial fiber to pultrude sufficient quantities to fabricate multiple blade sets. IACMI believes, with further development in packaging of the textile PAN carbon fiber, that this material can be successfully pultruded for large volume applications in wind turbines. In terms of the split between the low cost carbon fiber and the switch to a pultrusion process, when compared to the baseline, 16.5% can be assigned to the fiber, and the other 43.5% to use of the pultrusion process.

Carbon Fiber Spar Cap Embodied Energy Comparisons

As shown in Figure 18 a comparison of the embodied energies for the four spar cap variants confirms the lowest embodied energy for fiberglass spar cap due to the inherently low embodied energy of fiberglass itself at 50 MJ/kg compared with that for Standard carbon fiber at 1166 MJ/kg. For the LCCF fibers the embodied energies are lower than for the standard carbon fiber at 896 MJ/kg for the woven product form used in the VARTM processes, and 860 MJ/kg for the tow product form used in the pultrusion process. This difference in carbon fiber embodied energies is reflected in the relative heights of the blue bars in Figure 18.

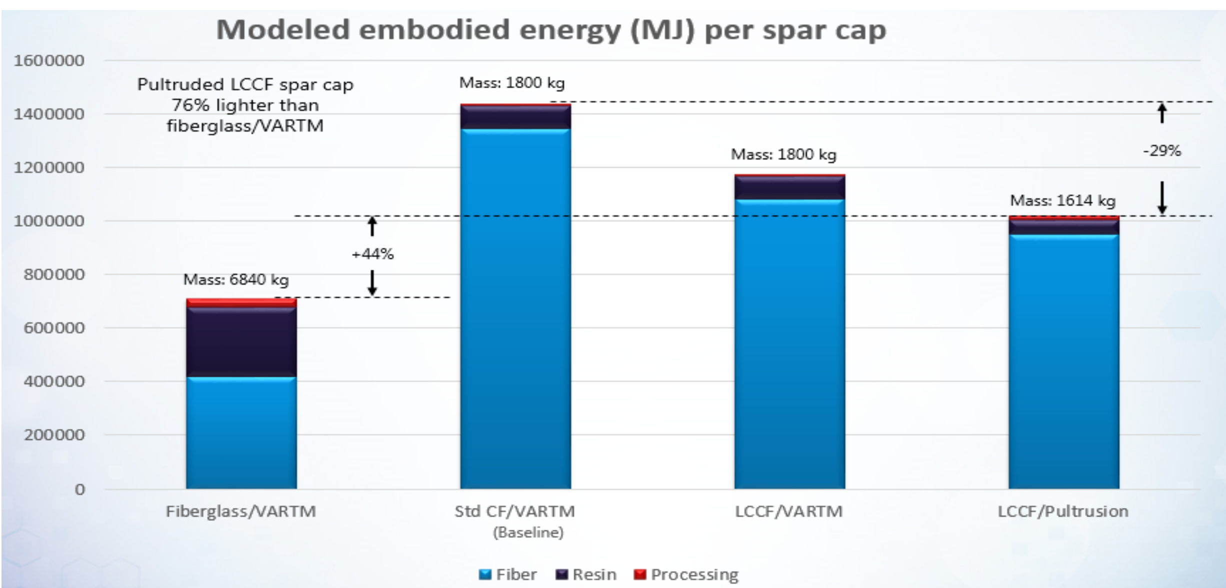


Figure 18. Comparative embodied energies for the four spar cap cases.

The lower height of the pultruded spar cap blue bar in comparison with the other LCCF spar caps is due to 1) the pultruded spar cap having a higher fiber volume, 58% versus 50%, and a lower scrap rate, 3 % versus 5%, and therefore less resin mass, and 2) no embodied energy due to the weaving process, which adds 36 MJ/kg. The resin embodied energy is significantly higher for the fiberglass spar cap versus that for the carbon fiber spar cap because of the sheer weight of the resin required in the VARTM fiberglass spar cap which is significantly heavier due to the stiffness differences between glass and carbon fibers. In the current analysis, the resin weight in the fiberglass spar cap was 2298 kg whereas for the VARTM carbon fiber spars the comparable resin weight was only 762 kg. While none of the carbon spar cap variants have lower embodied energy than the fiberglass version, the textile PAN low cost carbon fiber VARTM version has 18.3% lower overall embodied energy than the baseline and the pultruded version has 29% lower embodied energy than the baseline.

Section 4: Conclusions and Recommendations

Molded part cost is a primary metric in the analysis of whether a composite component is used in an industrial application, such as a wind turbine or automobile. Technical advances that reduce material costs and cycle times, and improve material utilization (reduced scrap) play an important role in improving the value proposition offered by advanced composites, and in particular, carbon fiber composites. Reducing the embodied energy in composites is also significant, as this improves the point during product use where the overall energy balance becomes positive. The baseline metric established by IACMI serve as a reference point for measuring the impact of these advances.

The DuPont-led IACMI project on Rapid Fabric Forming (RFF) shows great promise on several fronts. The flexible tow, combined with near net-shape layup and selective tacking points, allows for more complex structures and better material utilization versus conventional stiff thermoplastic fabric prepregs (organosheet). This improvement in material utilization is principally responsible for the 20% embodied energy reduction, and the scrap reduction combined with a lower cost material form ($22.04/kg vs $29.75/kg), combine to yield a 42% cost reduction over the baseline process and material.

Further work with this material is recommended, including detailed design of a complex part like the control arm, prototype molding, and validation of the material properties and improved costs and embodied energy. This should be compared with incumbent materials and processes, like cast iron or die-cast aluminum for this application.

For the wind turbine spar cap application, the pultrusion process, combined with the use of the textile PAN-based carbon fiber (low cost carbon fiber), offers the wind industry the opportunity to overcome a significant cost hurdle preventing widespread use of carbon fiber for utility scale blades. While most producers use fiberglass-based VARTM processed spar caps, several OEM's have specified carbon fiber, with at least one employing standard carbon fiber in pultruded form. The spar cap costs for the baseline 61.5m blade via the VARTM process for traditional carbon fiber and low cost carbon fiber are $49,000 and $41,000, respectively, both a premium to an equivalent fiberglass/VARTM cap at $29,000. Though not presented in this report, a pultruded spar cap made from traditional PAN-based industrial carbon fiber is approximately $30,000 or just slightly above the fiberglass spar cap.

Combining the two innovations detailed herein results in a spar cap cost of $19,500, 60% lower than the baseline traditional PAN/VARTM combination and 34% lower than the fiberglass/VARTM option. The key factors contributing to this include the use of a carbon fiber that costs $11.00/kg (versus $17.60/kg) in an as-produced format with no additional weaving cost, a higher fiber volume due to the pultrusion process, lower tooling costs, and significantly lower labor costs with the elimination of layup and bagging of the spar cap. The embodied energy of the pultruded low cost carbon fiber spar cap is 29% lower than the baseline carbon fiber version, yet still 44% higher than the fiberglass version. This gap against fiberglass will be difficult to overcome; fortunately, in 5 MW wind turbines that use the 61.5m blades, the additional embodied energy represented by the carbon fiber spar caps is returned within the first weeks of operation of the turbine, which is expected to produced energy for 20 years or more.

The experience with using the low cost carbon fiber with pultrusion is relatively limited, and needs additional development. IACMI is already working on improved packaging of the fiber that should enhance handling during pultrusion. The pultruded profiles need to be tested for mechanical performance, including fatigue, then incorporated into blades tested for overall stiffness and fatigue life.

These are recommended tasks for NREL to pursue. If the advancements demonstrated in the 9m blade project are validated in follow-on projects, the potential cost savings will be very attractive to wind turbine OEMs.

The baseline cost and energy metrics developed by IACMI, the ORNL cost model, and the embodied energy model developed by ORNL should be used on other IACMI projects, as IACMI and industry partners continue to reduce both costs and energy of advanced composites.

Appendix A: Cost Model Inputs

Cost model inputs for the RFF vs. Organosheet cases:

		CONTROL ARM	CONTROL ARM
		BASELINE	**RFF**
Part Variables			
	Length (mm)		
	Width (mm)		
	Thickness (mm)		
	Surface Area (mm^2)		
	Volume (mm^3)		
	Trim Length (mm)		
	Weight (kg)	5	5
Preform Process Variables			
	Material Density (gm/cc)	1.48	1.48
	Fiber Density (gm/cc)	1.78	1.78
	Resin Density (gm/cc)	1.14	1.14
	Process Time (min)		
	Preform Weight (lbs)	7.14	5.37
	Carbon Fiber Cost ($/lb)	$13.50	$10.00
	Fiber Loading (vol. %)	53%	53%
	Binder/Mold Release Cost ($/lb)		
	Scrap rate (%)	30%	6.9%
	Study Volume (parts/yr)	400,000	400,000
	No. Labor at Cell	2	3
	Preform Energy Useage (kW-hr/cell hr)		
	Preform Tooling Cost ($)		
	Preform Tooling Life (# parts)		
	Preform Cell Size (sq. ft)		
Molding Variables			
	Press Size (tons)	1000	1000
	Process Time (min)	2.0	2.0

	Resin Wt (lbs)	0.00	0.00
	Resin Cost ($/lb)	0	0
	Core Wt (lbs)	0.0	0.0
	Core Cost ($/ft2)	0.0	0.0
	Core Area (ft2)	0.0	0.0
	Tooling Cost ($)	$250,000	$250,000
	Molding Tooling Life (# of parts)	500,000	500,000
	Molding Scrap Rate (%)	3.0%	3.0%
	No. Labor at Cell	2.0	2.0
	Molding Energy Useage (kW-hr/cell hr)	0	0
	Molding Cell Size (sq. ft)	2000	2000
Trimming Variables			
	Process Time (min)	2	2
	Trimming Scrap Rate (%)	1.0%	1.0%
	No. Labor at Cell	1.0	1.0
	Trimming Energy Usage (kW-hr/cell hr)	0	0
	Trimming Cell Size (sq. ft)	1,100	1,100
Business Variables			
	Burdened Labor Rate ($/hr)	$26.00	$26.00
	Indirect Personnel (% Direct Labor)	40%	40%
	Energy Cost ($/kw-hr)	$0.06	$0.06
	Capital I & M Cost (% Capital)	3.0%	3.0%
	SG&A Rate (%)	4.0%	4.0%
	Sales Markup Rate (%)	10.0%	10.0%
	Capital Costs		
	Preforming Cell ($)	$200,000	$500,000
	Molding Cell ($)	$1,000,000	$1,000,000
	Trimming Cell ($)	$200,000	$200,000
	Interest Rate (%)	7.0%	7.0%
	Capital Payback Period (yrs)	8	8
	Tooling Payback Period (yrs)	3	3
	Preform Corporate Allocation (%)	20.0%	20.0%
	Molding Corporate Allocation (%)	20.0%	20.0%
	Trimming Corporate Allocation (%)	20.0%	20.0%

Cost model inputs for the four spar cap cases:

Spar Caps					
Baseline:	Carbon UD NCF	1800kg mass per cap			
	Also calculate glass fiber UD NCF, based on TPI ratio of 3.8x (glass to carbon fiber)	6840 kg mass per cap			
First alternative:	Carbon UD NCF using LCCF	1800 kg			
Second alternative:	Carbon LCCF via pultrusion	1614.5kg			
	w/scrap	1664kg			
Pultrusion data:	30cm wide x 4mm thick	continuous, wound on large spools			
	1.55 density				
	1.0m/minute pultrusion speed				
production rate:	1.86kg/min				
at 85% uptime	2276 kg/day per line	(24 hour operation)			
at 250 days/yr	569,000 kg/yr/line				
900 blades requires	2,995,200kg/yr	(2 spar caps per blade)			
lines required:	5.26	(assume 6 lines)			
capital cost per line:	$500,000				
tooling cost per line:	$100,000				
operators per line:	2				
no trimming required					

		SPARCAP/Baseline	**SPARCAP/ Baseline**	**SPARCAP**	**SPARCAP**
		UD Fiberglass NCF/VARTM	**50K Commercial/ VARTM**	**LCCF VARTM**	**LCCF PULTRUSION**
Part Variables					
	Length (mm)	61500	61500.0	61500.0	61500.0
	Width (mm)				
	Thickness (mm)				

	Surface Area (mm^2)				
	Volume (mm^3)				
	Trim Length (mm)				
	Weight (kg)	6840	1800.0	1800.0	1614.5
Preform Process Variables					
	Material Density (gm/cc)	1.80	1.50	1.50	1.54
	Fiber Density (gm/cc)	2.54	1.78	1.78	1.78
	Resin Density (gm/cc)	1.2	1.20	1.20	1.23
	Process Time (min)	115.0	115.0	115.0	
	Preform Weight (lbs)	4652	1080.00	1080.00	1,080.00
	Carbon Fiber Cost ($/kg)	$1.98	$27.30	$21.56	$11.00
	Fiber Loading (vol. %)	50.0%	50.0%	50.0%	58%
	Binder/Mold Release Cost ($/lb)		$0.00	$0.00	$0.00
	Scrap rate (%)	5%	5.0%	5.0%	3.0%
	Study Volume (parts/yr)	925	925	925	925
	No. Labor at Cell	16	16.0	16.0	2
	Preform Energy Useage (kW-hr/cell hr)				
	Preform Tooling Cost ($)		$0	$0	
	Preform Tooling Life (# parts)				
	Preform Cell Size (sq. ft)		0	0	
Molding Variables					
	Press Size (tons)				
	Process Time (min)	422.5	422.5	422.5	
	Resin Wt (lbs)	2188	720.00	720.00	534.50
	Resin Cost ($/kg)	$3.63	$3.63	$3.63	$3.63
	Core Wt (lbs)		0.0	0.0	0.0
	Core Cost ($/ft2)		0.0	0.0	0.0
	Core Area (ft2)		0.0	0.0	0.0
	Tooling Cost ($)	$375,000	$375,000	$375,000	$250,000
	Molding Tooling Life (# of parts)	450	450	450	

	Molding Scrap Rate (%)	0.30%	0.3%	0.3%	
	No. Labor at Cell	22	22.0	22.0	
	Molding Energy Useage (kW- hr/cell hr)				
	Molding Cell Size (sq. ft)				
Trimming Variables					
	Process Time (min)	330	330	330	
	Trimming Scrap Rate (%)	0.3	0.3%	0.3%	
	No. Labor at Cell	2	2.0	2.0	
	Trimming Energy Usage (kW-hr/cell hr)		0	0	
	Trimming Cell Size (sq. ft)	699	699	699	
Business Variables					
	Burdened Labor Rate ($/hr)	$26.00	$26.00	$26.00	$26.00
	Indirect Personnel (% Direct Labor)	40%	40%	40%	40%
	Energy Cost ($/kw-hr)	$0.06	$0.06	$0.06	$0.06
	Capital I & M Cost (% Capital)	3.0%	3.0%	3.0%	3.0%
	SG&A Rate (%)	4.0%	4.0%	4.0%	4.0%
	Sales Markup Rate (%)	10.0%	10.0%	10.0%	10.0%
	Capital Costs				
	Preforming Cell ($)	$0	$0	$0	
	Molding Cell ($)	$100,000	$100,000	$100,000	
	Trimming Cell ($)	$25,000	$25,000	$25,000	
	Interest Rate (%)	7.0%	7.0%	7.0%	7.0%
	Capital Payback Period (yrs)	8	8	8	8
	Tooling Payback Period (yrs)	3	3	3	3
	Preform Corporate Allocation (%)	20.0%	20.0%	20.0%	20.0%
	Molding Corporate Allocation (%)	20.0%	20.0%	20.0%	20.0%

	Trimming Corporate Allocation (%)	20.0%	20.0%	20.0%	20.0%
NOTE:	SPAR CAP (PREFORM):		TOOL PREP & LAYUP OPERATIONS		
	SPAR CAP (MOLDING):		INFUSE, CURE & DEBAG		
	SPAR CAP (TRIMMING):		TOUCHUP		

Appendix B: Embodied Energy Calculations

Embodied energy calculations for RFF and organosheet processes:

		Calculator/Lit review inputs	Process/Material Embodied energyMJ/kg	Yield	Embodied energy for final part (MJ/kg)	Scrap rate
Organo sheet						
	CF & PA 66				5862.93	
Step 1	CF (organo sheet)				5437.37	
Step 2	PA66 (organo sheet)				425.56	
Step 3	PA Film Casting	Prepregs, Manual, Fabric (TP)	24	85%	72.56	
Step 4	CF Weaving	Dry weave	36	98%	167.88	
Step 5	Cut net shape	Gerber cutter		70%	0.90	7.08
Step 6	Net shape preform					30.00
Step 7	Preheating	IR oven	1.2		6.00	0
Step 8	Compression Molding	Compression molding	27.7		138.50	0
Step 9	Final trim	Router			0.49	0
	Total embodied energy for 5kg part		88.9		**6249.26**	
	Embodied energy per kg				1249.85	
RFF laydown						
	CF & PA 66				4623.85	
Step 1	CF (RFF)				4314.20	
Step 2	PA66 (RFF)				309.65	
Step 3	Tow coating CF			93%		
Step 4	Tow coating Nylon66	Pultrusion	9.7	88%	57.23	
Step 5	RFF Laydown	Dry weave	36	98%	193.34	8.97
Step 6	Trim	Gerber cutter		95%	1.22	2.00
Step 7	Net shape preform					5.00
Step 8	Preheating	IR oven	1.2		6.00	0
Step 9	Compression Molding	Compression molding	27.7		138.50	0
Step 10	Final trim	Router			0.49	0
	Total embodied energy for 5kg part	Total processing embodied energy	74.6		**5020.63**	
	Embodied energy per kg				1004.13	80%
				Difference	**245.73**	

Embodied energy calculations for RFF and organosheet processes (detailed):

	7.69				Process (Yield)	
	PA Film Casting (85%)				MJ/kg	
	Prepregs, Manual, Fabric (TP)				kg	
	24	Cut net (70%)			Associated embodied energy for our calc	
	3.02	Gerber cutter			Scrap rate (%)	
	72.56	Taking power = 17.2 kW for 2min				
	CF Weaving (98%)	7.14				
	Dry weave	F:R=4.57:2.57				
	36	0.896				
	4.66					
	167.88	7.08				
			Final net shape	Preheating (IR)	Compression molding	Final Trim
				1.2	27.7	Power = 6.6 kW
			5	5	5	5
5.90			F:R=3.2:1.8	6	138.5	0.491
Tow coat (CF) (93%)						
Pultrusion			30.00			
9.7			5.00	0	0	0
3.70	RFF (98%)	Trim (95%)				
	Dry weave	Gerber cutter			Total embodied energy for traditional organo sheet process with 5kg final part weight (MJ/kg)	6249.26
Tow coat (PA) (88%)	36	Taking power = 17.2 kW for 2min			Total embodied energy for DuPont RFF process with 5kg final part weight (MJ/kg)	396.78
2.20	5.37	5.26			Process 1: Overall manufacturing scrap rate	34.95
	F:R=3.44:1.93	F:R=3.37:1.89			Process 2: Overall manufacturing scrap rate	15.25
	193.34	1.22			Difference	19.70
57.23	8.97	2.00			Process 1: Final step scrap rate	30.00
					Process 2: Final step scrap rate	5.00
Embodied energy of materials: CF & PA66					Difference	25.00
CF=1166MJ/kg; Nylon 66 =140.75MJ/kg	Process 1	Process 2				
CF	5437.37	4314.20				
Nylon 66	425.56	309.65				

Embodied energy calculations for four spar cap cases:

		Process/Material (MJ/kg)	Density (g/cc)	Weight (kg)	Embodied energy (MJ)	Scrap rate	Normalized
Process Spar Cap NCF-VARTM (Fiberglass)							
50% vol fraction = 68:32 wt fraction							
Fiber	0.68						
Resin	0.32						
Step 1	Glass UD NCF	86	2.54	4884	420003.36		
Step 2	Epoxy	113	1.2	2298	259701.12		
Step 3	VARTM	4		7182	28728.00	5%	
				6840			
				Total embodied energy for final part weight of 6840kg	**708432.48**		100%
				Embodied energy per kg	103.57		100%
Spar Cap NCF-VARTM (Carbon)							
50% vol fraction = 59.7:40.3 wt fraction							
Fiber	0.597						
Resin	0.403						
Step 1	CF 50k	1191	1.78	1128	1343841.03		
Step 2	Epoxy	113	1.2	762	86068.71		
Step 3	VARTM	4		1890	7560.00	5%	
				1800			
				Total embodied energy for final part weight of 1800kg	**1437469.74**		100%
				Embodied energy per kg	798.59		100%
Spar Cap LCCF-VARTM							
50% vol fraction = 59.7:40.3 wt fraction							
Fiber	0.597						
Resin	0.403						
Step 1	LCCF	896	1.78	1128	1010983.68		
Step 2	Epoxy	113	1.2	762	86068.71		
Step 3	VARTM	4		1890	7560.00	5%	
				1800			
				Total embodied energy for final part weight of 1800kg	**1104612.39**		77%
				Embodied energy per kg	613.67		77%
Spar Cap LCCF-Pultrusion							
58% vol fraction = 66.5:33.5 wt fraction							
Fiber	0.665						
Resin	0.335						
Step 1	LCCF	860	1.78	1107	951880.68		
Step 2	Polyurethane	93	1.23	557.5800451	51854.94		
Step 3	Pultrusion	9.7		1664.418045	16144.86	3%	
				1614.485504			
				Total embodied energy for final part weight of 1614kg	**1019880.48**		71%
				Embodied energy per kg	631.71		79%