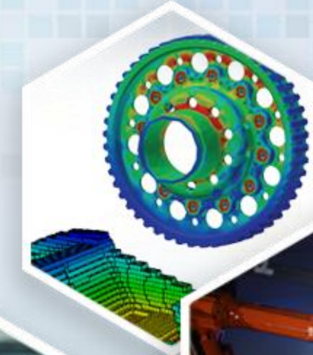
IACMI Baseline Cost and Energy Metrics

March 2017


Notice

This document is being published on March 29, 2017, following presentation at the IACMI members meeting February 1-2, 2017, and comment period following that meeting.

Readers are encouraged to send questions and comments to:

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Table of Contents

Objectives of Metrics Study

The Overall Objective of this study was to establish baseline metrics for IACMI with the following sub-objectives

- Establish the state of the art as of June 2015 (launch date of IACMI) in composite part size, complexity and performance requirements for automobile, wind turbine blade, and compressed gas storage applications
- Determine the cost metric in terms of $/kg part weight for representative composite components and manufacturing methods as of June 2015
- Determine the embodied energy metric in terms of MJ/kg part weight for the components and manufacturing processes selected for estimating the cost metric
- Perform sensitivity studies to assess the dependence of these metrics on several variables such as manufacturing rate and waste
- Track changes in metric values as new projects develop data, towards meeting the goals of
  - Reducing production cost of finished carbon fiber composites for targeted applications (vehicles, wind, high-pressure gas storage at a minimum) by >25% in five years, on a pathway to a reduction of cost >50% over ten years
  - Reducing the embodied energy (and associated greenhouse gas emissions) of carbon fiber composites by 50% compared to today's technology on a pathway to 75% reduction in ten years Embodied energy refers to the energy required to make the materials and manufacture a composite part, it does not include distribution, use phase or end-of-life energy consumption of a product

  subject to the constraint imposed by

  - Need to demonstrate technologies, at sufficient scale, for >80% recyclability or reuse of fiber reinforced polymer composites in five years into useful components with projected cost and quality at commercial scale competitive with virgin materials on a pathway to >95% recyclability or reuse starting in ten years.

Methodology

IACMI has an initial three market areas of focus, where advanced composites (and especially carbon fiber composites) are of interest:

Vehicles – principally passenger cars and light trucks, but also heavy trucks

Wind turbine blades – primarily utility scale (>1 MW)

Compressed gas storage – Type IV and V cylinders for natural gas and hydrogen

For each of the above markets, representative components or finished products were selected for calculating baseline values of cost and embodied energy, expressing the state-of-the-art as of June, 2015 (official start date of IACMI).

IACMI experts conducted extensive reviews of the literature and combined this with interviews and plant visits with multiple companies in each market sector to understand the inputs to the models.

IACMI worked closely with experts at Oak Ridge National Laboratory (ORNL) to calculate the baseline costs and embodied energy, using cost and energy models developed by ORNL.

Wind Turbines

Wind Turbine Blade Overview

Wind energy is an increasing component of the U.S. and worldwide energy portfolio. A key driver is reducing the Levelized Cost of Energy (LCOE), represented in $/kw-hr:

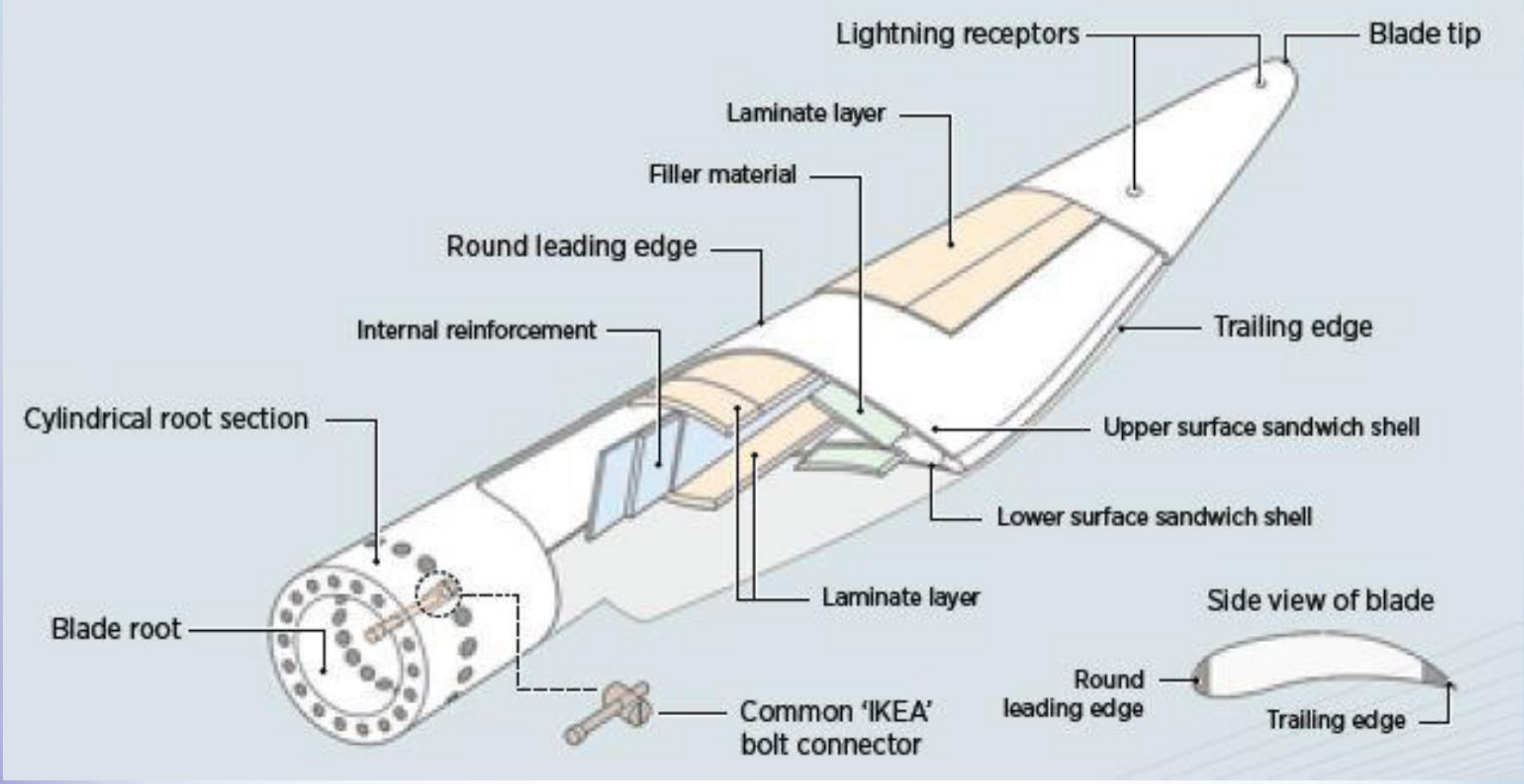
$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Improvements in LCOE can be achieved by increasing the length of turbine blades, reducing the materials and manufacturing costs, or lowering the erection and in-service costs.

For the baseline modeling of wind turbine blade costs and embodied energy, the National Renewable Energy Lab (NREL) 61.5m blade design was selected. This blade represents the size required for a 5MW turbine and is a good proxy for both land and offshore utility scale deployment. The design has cored fiberglass reinforced skins and unidirectional carbon fiber spar caps with a box-beam construction (double shear webs).

The baseline is done on a target volume of 900 blades (300 systems) annually. Cycle times and material costs for the various steps of blade construction are based on discussions with key blade fabricators.

Wind Turbine Blade Design



NREL Wind Blade Manufacturing Cost Model

12.2 ton 61.5m CF Spar Cap Blade
- ✓ 1.8 ton CF spar cap
- ✓ 50K Tow CF Fabric: $31.25/kg
- ✓ Epoxy Resin: $3.63/kg
- ✓ Tooling Cost: $80M (~$5M Spar Cap)
- ✓ Annual Production Vol. (~ 900 blades)

Kitting (43)

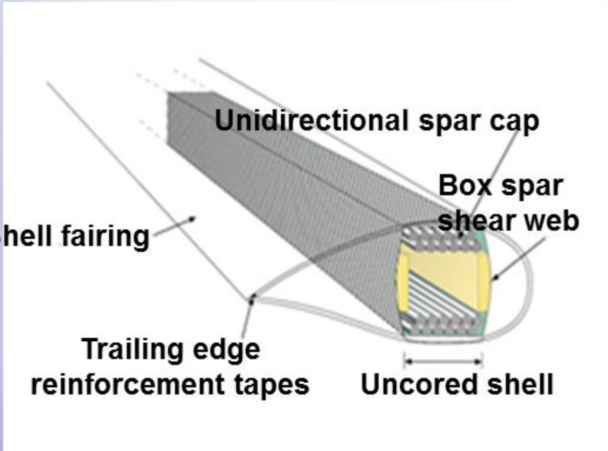
Root Prefab (HP/LP) (26)
LE Shear Web (26)
TE Shear Web (14)
Spar Cap (HP/LP) (158)
Balance Box (3)
Root Close-Out (9)
Mold Skins (HP/LP) (292)

Carbon Fiber

"Mold" Steps
Mold Prep
Layup/Cure Prep
Infusion
Cure
Debag/Demold
Assembly Prep
Inspection

Blade Assembly (72)

Post-Mold Rework (26)
Trim/Grid Fair (110)
Over Laminations (45)
Post Cure (12)
Root Machining (31)
Install T-Nuts (44)
Install Root Close Out (10)
Scuff Sand (53)
Paint (55)
Seration/VG Installation(27)
Weight and Balance (22)
Final check-off for Ship (32)



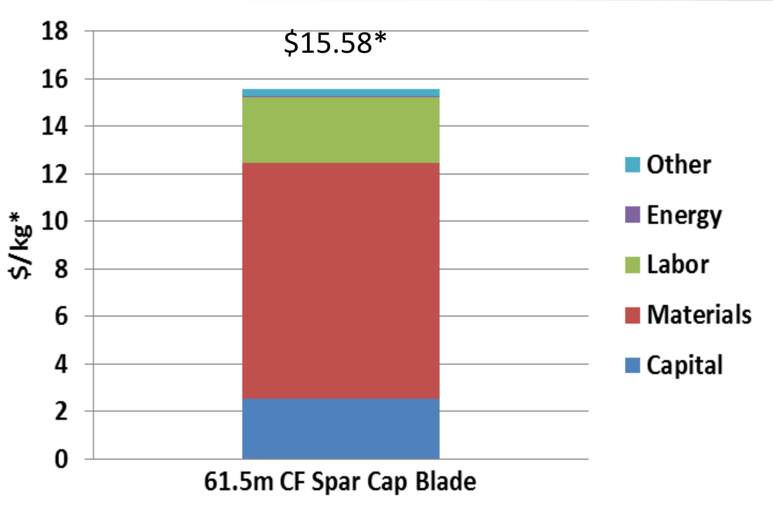
() – Values indicate total labor hours per 61.5m blade
Total labor hours/blade = 1,113 hrs

Source: ORNL 61.5m 12.2 ton Spar Cap Carbon Fiber Blade Competitiveness Analysis Cost Model (2015)
Labor hours based on communication with major blade fabricator, Apr. 23, 2015

Wind Blade Cost Analysis (baseline)

- Cost estimates based on a 61.5m12.2 ton blade consisting of carbon fiber spar cap based on vacuum assisted resin transfer molding technology
- A detailed NREL discounted cash flow cost model consisting of 24 major manufacturing steps adapted by ORNL was used** – input data used were validated by one of the major U.S. blade manufacturers
- Carbon fiber spar cap weight = 1.8 tons with fiber ($31.25/kg) and epoxy resin ($3.63/kg) weight ratio of 74:26

  - 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

** Das, S. et al. (2016). "Clean Energy Manufacturing Analysis Center (CEMAC): 2015 Research Highlights,"NREL/BR-6A50-65312| ORNL/SR-2016/98, March.

Vehicles

Vehicles Overview

The vehicles market represents a significant opportunity for advanced composites, but is currently limited by high part costs and slow cycle times.

IACMI is focused on reduction of part costs via lower cost materials, more efficient design, and faster manufacturing processes. For the purposes of baseline evaluation, the following components and processes were selected, based on being in production at some reasonable volume or at a level of prototype maturity to represent state-of-the art as of June 2015:

Floor pan for mid-sized sedan – High Pressure Resin Transfer Molding (and related technologies like wet pressing)

Hood inner panel – Prepreg Compression Molding

Rear closure (tailgate) inner panel for full sized SUV – Injection over-molding

All baseline modeling is done on a target volume of 100,000 units annually. Cycle times are based on multiple discussions with OEMs and Tier 1 suppliers. All scrap is assumed to be landfilled for the baseline processes.

High Pressure RTM Floor Pan

Floor pan prototype produced via HP-RTM

Dimensions: 1500mm (L) x 1200mm (W)
Thickness (average): 2.0mm

Reinforcement: Multi-axial carbon fiber non-crimp fabric

Resin: Liquid epoxy resin/hardener

Process: Mechanical preforming/trimming followed by high-pressure resin transfer molding (HP-RTM)

Cycle time: preforming – 5 minutes
molding – 9 minutes

Prepreg Compression Molding - Hood

Hood inner panel via compression molding

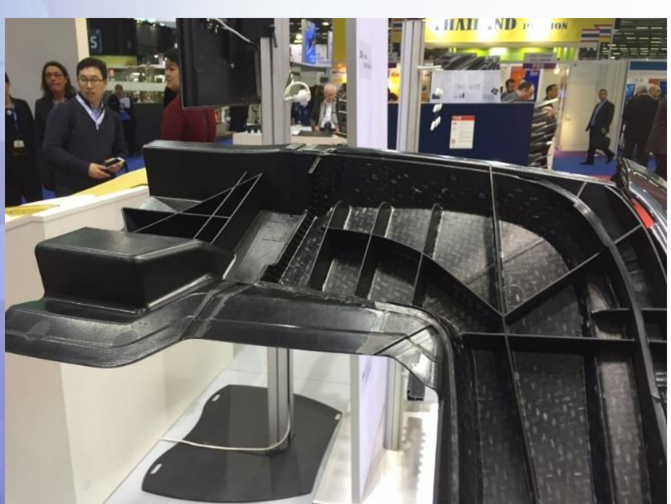
Dimensions: 1015mm (L) x 1525mm (W)
Thickness (average): 1.2mm

Material: Unidirectional carbon fiber/epoxy tape

Process: Automated pattern cutting, hand layup and low pressure preforming, followed by isothermal pressing in matched metal tooling.

Cycle time: preforming – 10 minutes
molding – 10 minutes

SUV Rear Closure Inner Panel



Rear closure inner panel produced via injection over-molding

Dimensions: 915mm (L) x 1220mm (W)
Thickness (average): 2.5mm

Thermoplastic glass or carbon woven fabric, impregnated with PP (organosheet), plus 30% long fiber reinforced PP

Process: Thermoformed organic fiber sheets, preheated and robotically inserted into mold, followed by injection of long fiber thermoplastic to achieve surface finish and detailed features (ribs, bosses)

Cycle time: preforming – 3 minutes
molding – 3.5 minutes

Automotive Part Cost Analysis (baseline)

PARAMETER	HPRTM (FLOORPAN)	INJECTION OVERMOLDING (DOOR INNER PANEL) -- CF	INJECTION OVERMOLDING (DOOR INNER PANEL) -- GF	PREGREG COMPRESSION MOLDING (HOOD INNER)
Part Weight (kg)	6.4	1.95	2.2	1.7
PREFORM				
Weight (fiber/resin) (kg)	4.1 (4.1/0)	0.5 (0.3/0.2)	0.6 (0.5/0.1)	1.9 (1.2/0.7)
CF Cost ($/kg)	$33.00	$37.40	$13.20	$26.40
Cycle Time (min)	5.0	3.0	3.0	10.0
Scrap Rate (%)	30%	20%	20%	30%
Energy (kWh/Cell-hr)	166	21	21	210
Capital ($M)	$1.5M	$0.5M	$0.5M	$0.5M
MOLDING				
Weight (fiber/resin) (kg)	2.6 (0/2.6)	1.5 (0.5/1.0)	3.7 (0.6/2.1)	1.9 (0/0)
Resin Cost ($/kg)	$8.82	$26.40	$6.60	NA
Cycle Time (min)	9.0	3.5	3.5	10.0
Scrap Rate (%)	3%	3%	3%	3%
Energy (kWh/Cell-hr)	250	35	35	48
Capital ($M)	$5.6M	$3M	$3M	$2.5M

Auto Part Dimensions (baseline)

Part Variables	Stacked Fabric Preform/HPRTM	Injection Overmolding	Prepreg/Compression Molding
	Floor Pan	SUV Rear Door Inner Panel	Hood Inner Panel
Length (mm)	1500.0	915.0	1015.0
Width (mm)	1200.0	1220.0	1525.0
Thickness (mm)	2.0	2.5	1.2
Surface Area (mm^2)	2,070,000.0	692,900.0	928,725.0
Volume (mm^3)	4,140,000.0	1,732,250.0	1,114,470.0
Trim Length (mm)	6000.0	6800.0	8000.0
Weight (kg)	6.38	1.95	1.72

Auto Preforming Process Variables (baseline)

	Stacked Fabric Preform/HPRTM	Injection Overmolding	Injection Overmolding	Prepreg/Compression Molding
Preform Process Variables	**Floor Pan**	**SUV Rear Door Inner Panel (CF)**	**SUV Rear Door Inner Panel (GF)**	**Hood Inner Panel**
Material Density (gm/cc)	1.78	1.12	1.28	1.54
Fiber Density (gm/cc)	1.78	1.78	2.54	1.78
Resin Density (gm/cc)	1.20	0.91	0.91	1.20
Process Time (min)	5.0	3.0	3.0	10.0
Preform Weight (kg)	4.15	0.47	0.60	1.89
Carbon Fiber Cost ($/kg)	$33.00	$37.40	$13.20	$26.40
Fiber Loading (vol. %)	50.0%	50.0%	50.0%	50%
Binder/Mold Release Cost ($/kg)	$0.00	$0.00	$0.00	$0.00
Scrap rate (%)	30.0%	20.0%	20.0%	30.0%
Study Volume (parts/yr)	100,000	100,000	100,000	100,000
No. Labor at Cell	2.0	2.0	2.0	2
Preform Energy Usage (kW-hr/cell hr)	166.2	21.0	21.0	210.0
Preform Tooling Cost ($)	$330,000	$75,000	$75,000	75,000
Preform Tooling Life (# parts)	500,000	500,000	500,000	500,000
Preform Cell Size (m^2)	140	93	93	93

Auto Molding and Trimming Variables (baseline)

Molding Variables	Stacked Fabric Preform/HPRTM	Injection Overmolding	Injection Overmolding	Prepreg/Compression Molding
	Floor Pan	SUV Rear Door Inner Panel (CF)	SUV Rear Door Inner Panel (GF)	Hood Inner Panel
Press Size (tons)	4,000	3000	3000	2500
Process Time (min)	9.0	3.5	3.5	10.0
Resin Wt (kg)	2.55	1.52	1.68	0.00
Resin Cost ($/kg)	$8.80	$13.20	$6.60	0
Core Wt (kg)	0.0	0.0	0.0	0.0
Core Cost ($/m2)	0.0	0.0	0.0	0.0
Core Area (mt2)	0.0	0.0	0.0	0.0
Tooling Cost ($)	$1,000,000	$850,000	$850,000	$350,000
Molding Tooling Life (# of parts)	300,000	500,000	500,000	250,000
Molding Scrap Rate (%)	3.0%	3.0%	3.0%	3.0%
No. Labor at Cell	2.0	2.0	2.0	2.0
Molding Energy Useage (kW-hr/cell hr)	249.7	34.8	34.8	48
Molding Cell Size (m^2)	370	185	185	185
Trimming Variables				
Process Time (min)	2	2	2	2
Trimming Scrap Rate (%)	1.0%	1.0%	1.0%	1.0%
No. Labor at Cell	1.0	1.0	1.0	1.0
Trimming Energy Usage (kW-hr/cell hr)	0	0	0	0
Trimming Cell Size (m^2)	102	102	102	102

Auto Production Capacity Utilization (baseline)

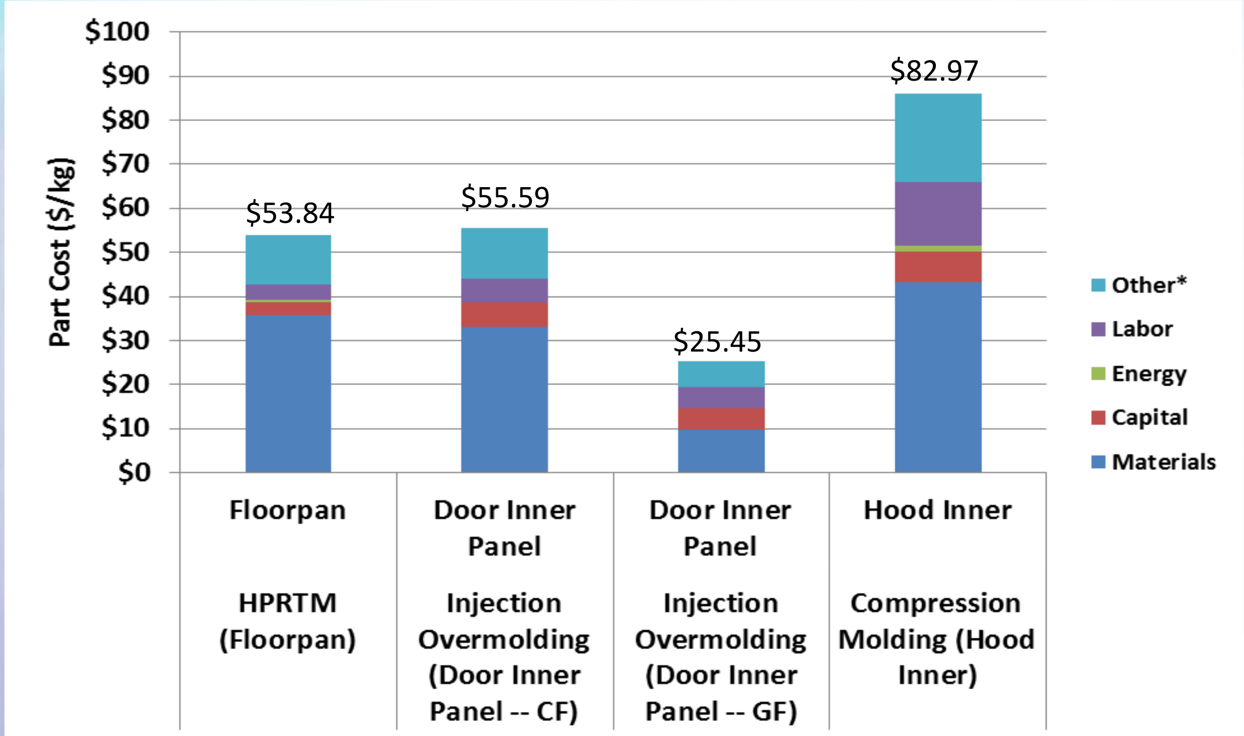
Annual Production Volume	100,000 parts
No. of Shifts/day	3
Total Working Days/yr	235
Machine uptime	85%
Total Annual Production Hours	4794

CELL	PARAMETER	Stacked Fabric Preform/HPRTM	Injection Overmolding	Injection Overmolding	Prepreg/Compression Molding
		Floor Pan	SUV Rear Door Inner Panel (CF)	SUV Rear Door Inner Panel (GF)	Hood Inner Panel
Preforming	Capital ($)	$1,500,000	$500,000	$500,000	$500,000
	Cycle Time (min)	5.0	3.0	3.0	10
	Machines Reqd. (#)	**2**	**1**	**1**	**2**
	Machine Utilization (%)	87%	52%	52%	70%
Molding	Capital ($)	$5,600,000	$3,000,000	$3,000,000	$2,500,000
	Cycle Time (min)	9.0	3.5	3.5	10.0
	Machines Reqd. (#)	**3**	**1**	**1**	**2**
	Machine Utilization (%)	78%	61%	61%	87%
Trimming	Capital ($)	$200,000	$200,000	$200,000	$200,000
	Cycle Time (min)	2	2	2	2
	Machines Reqd. (#)	**1**	**1**	**1**	**1**
	Machine Utilization (%)	70%	70%	70%	70%

Auto Business Variables (baseline)

Business Variables	Stacked Fabric Preform/HPRTM	Injection Overmolding	Injection Overmolding	Prepreg/Compression Molding
	Floor Pan	SUV Rear Door Inner Panel (CF)	SUV Rear Door Inner Panel (GF)	Hood Inner Panel
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	$0.06
Capital I & M Cost (% Capital)	3.0%	3.0%	3.0%	3.0%
SG&A Rate (%)	4.0%	4.0%	4.0%	4.0%
Sales Markup Rate (%)	10.0%	10.0%	10.0%	10.0%
Capital Costs				
Preforming Cell ($)	$1,500,000	$500,000	$500,000	$500,000
Press Cell ($)	$5,600,000	$3,000,000	$3,000,000	$2,500,000
Trimming Cell ($)	$200,000	$200,000	$200,000	$200,000
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

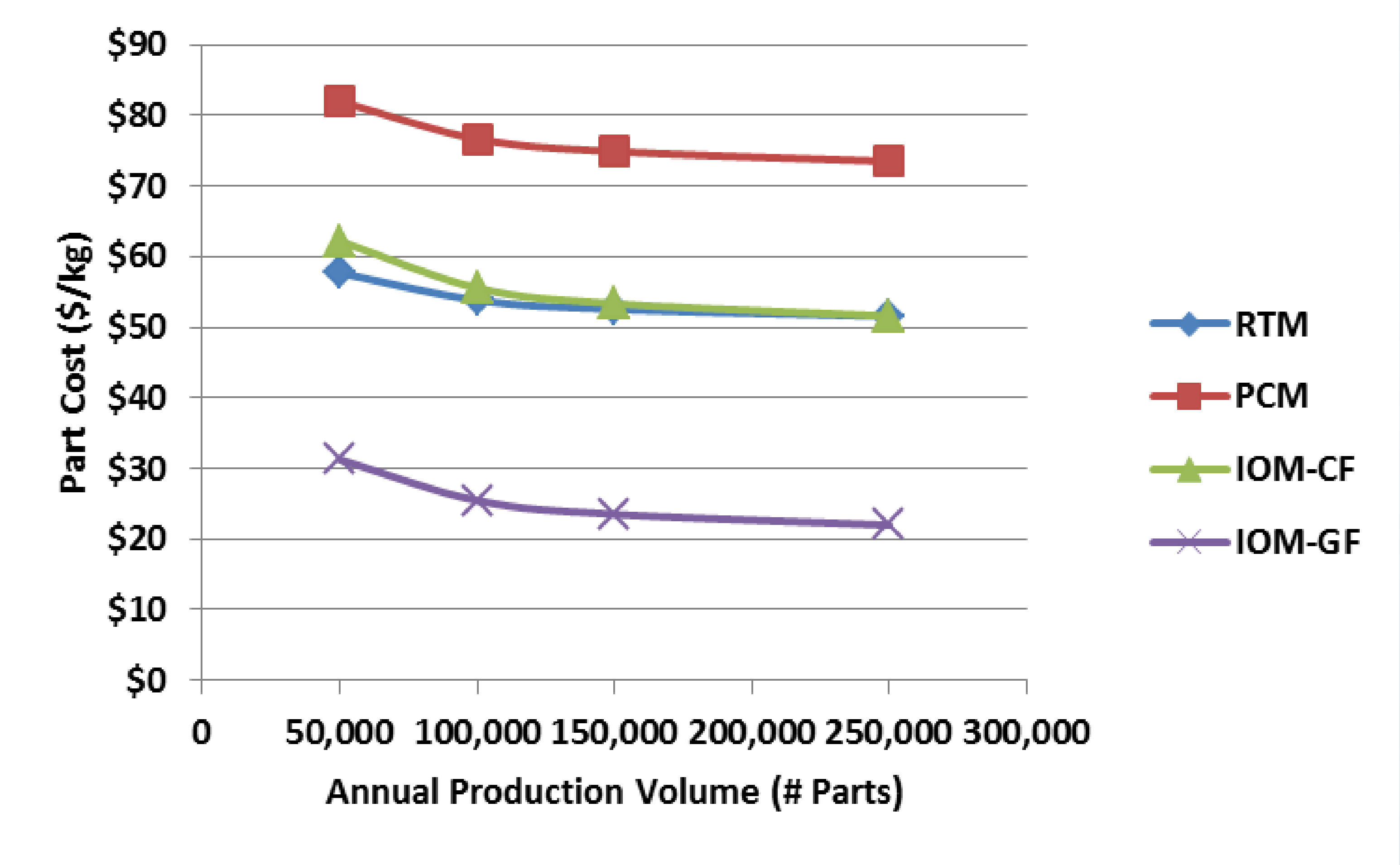
Automotive Part Cost



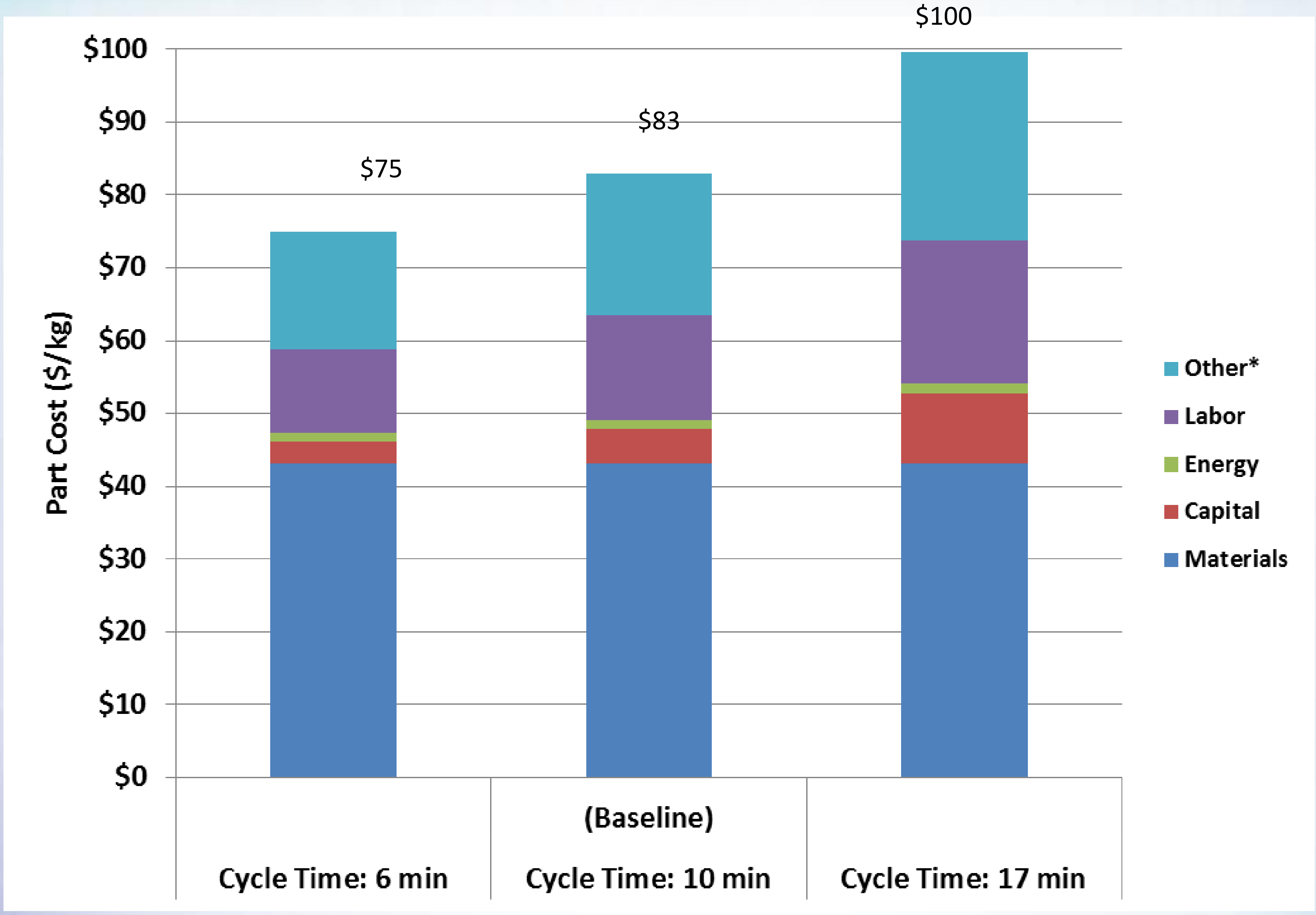
*Includes indirect labor overhead and corporate overhead

- Unit part cost decreases with part mass (Significantly lighter CF Injection Overmolding part cost similar to HPRTM due to lower scrap rate for the lighter part)
- Highest Compression Molding unit part cost as economies of scale least for the lightest part (cycle time maximum for the lightest part)
- Largest material cost share to total part cost – highest cost for Compression Molding for a higher level scrap generated (least in case of Injection Overmolding)
- Energy cost is the least contributor to total part cost

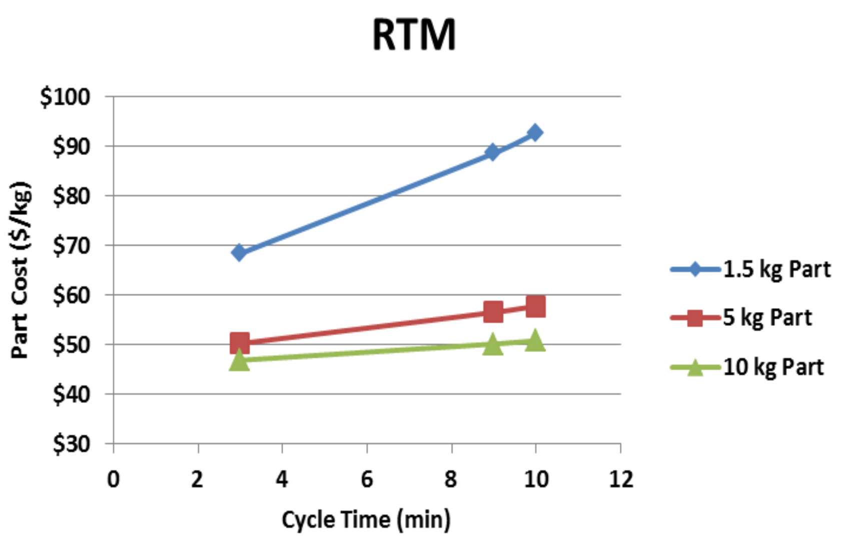
Annual Production Volume vs. Part Cost Sensitivity

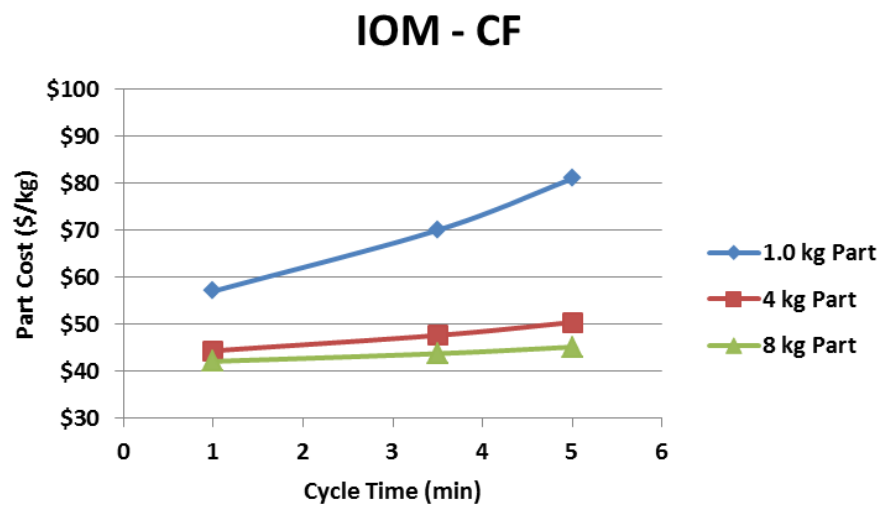


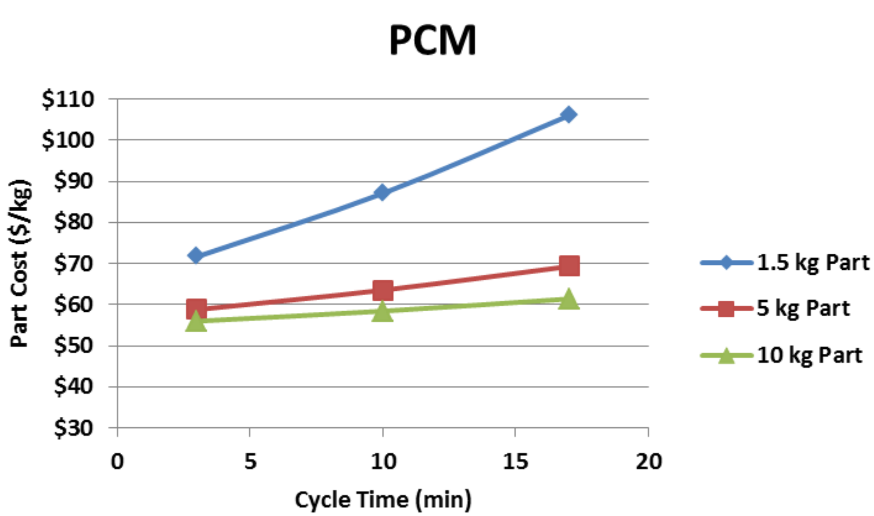
Prepreg Compression Molding – Cycle Time Cost Sensitivity

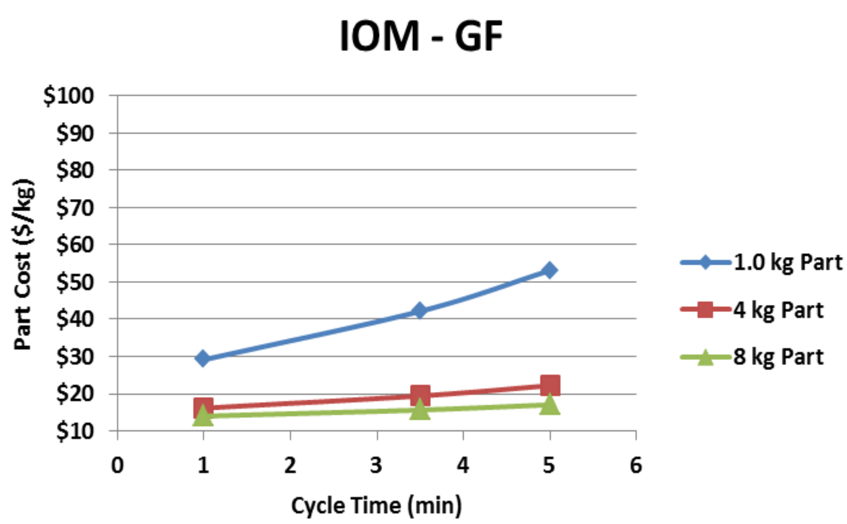


Cycle Time vs. Part Cost Sensitivity

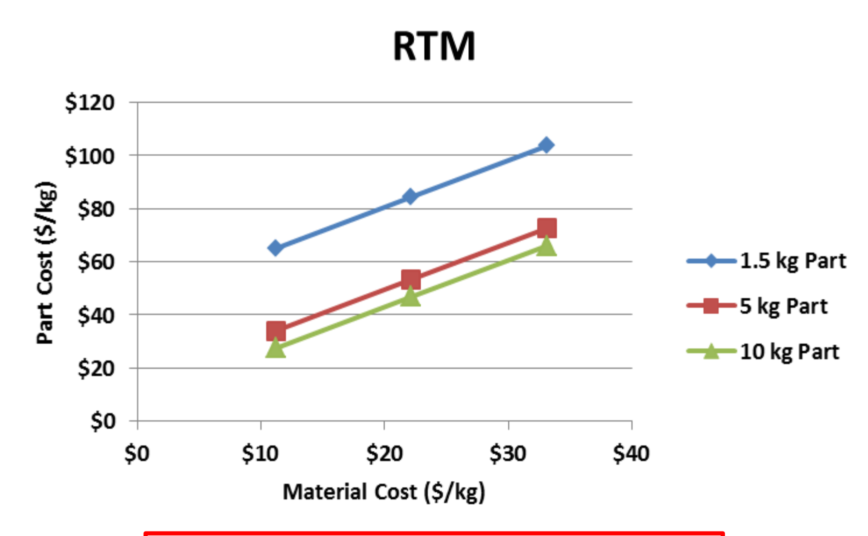




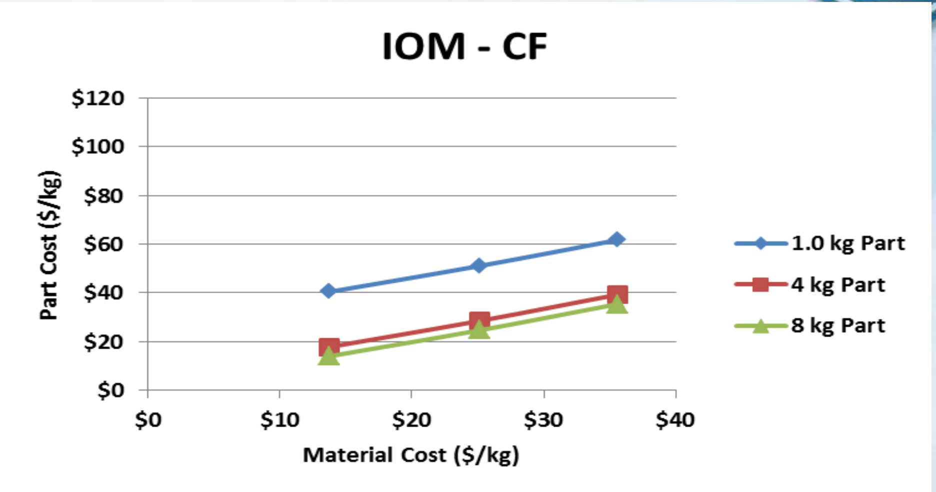




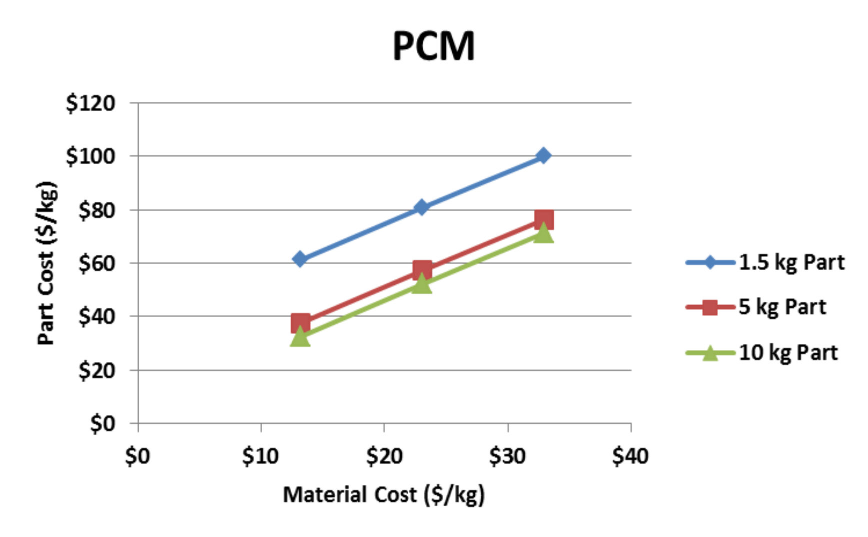
Material Cost vs. Auto Part Cost Sensitivity

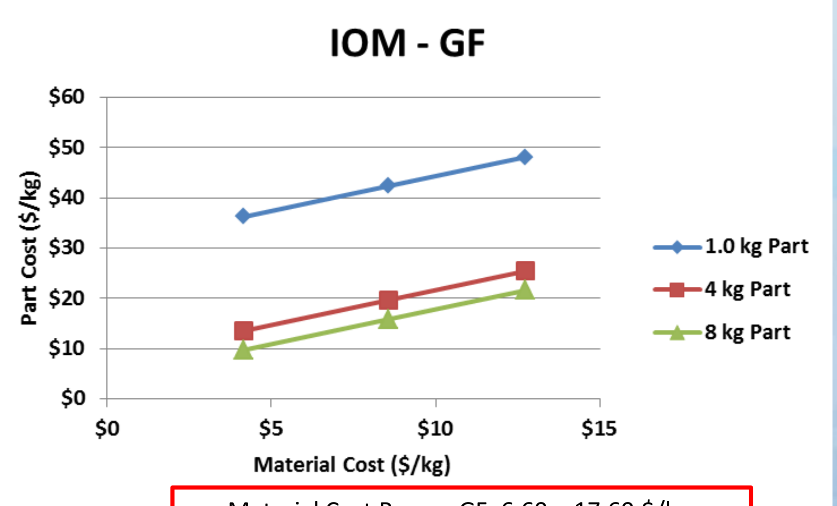


Material Cost Range: CF: 15.40 – 44.00 $/kg
Resin: 4.40 – 15.40 $/kg



Material Cost Range: CF: 15.40 – 44.00 $/kg
Resin: 13.20 – 33.00 $/kg

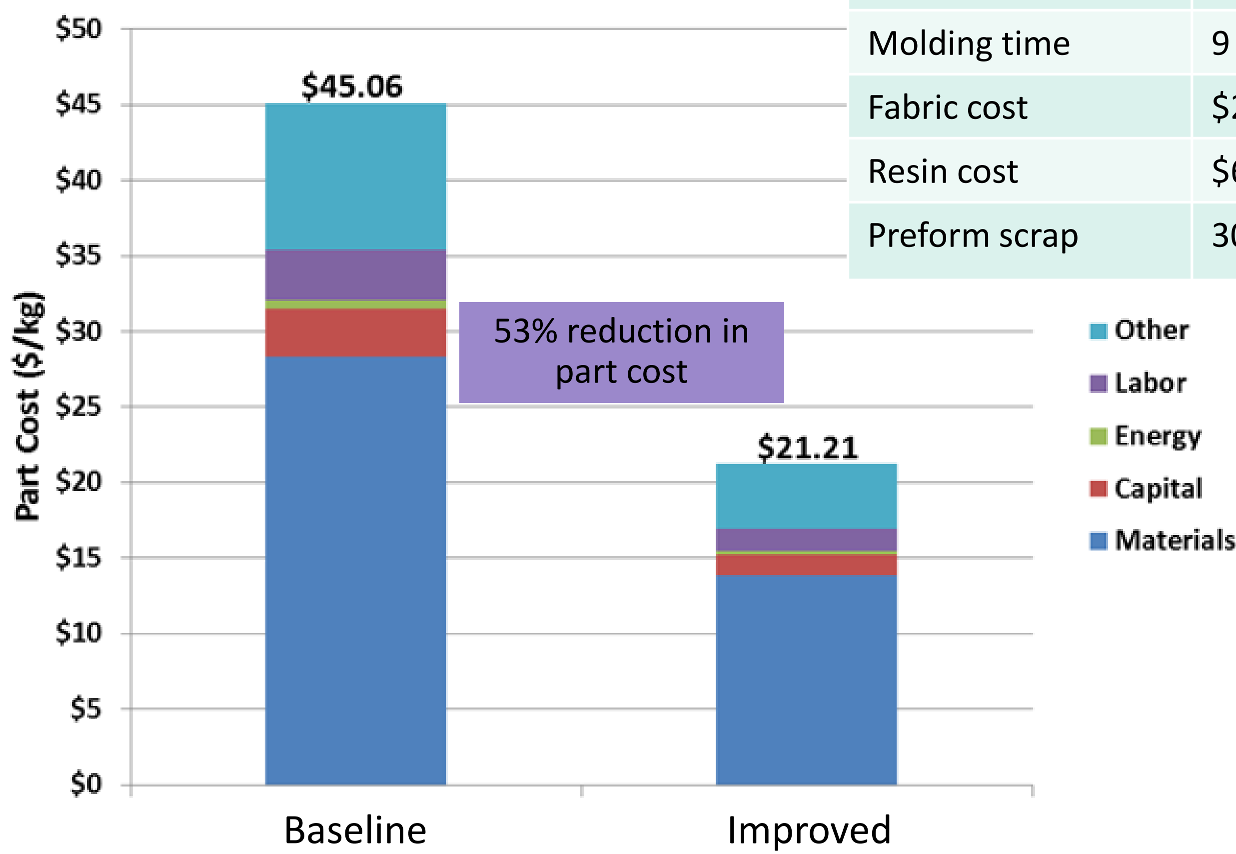




Material Cost Range: GF: 6.60 – 17.60 $/kg
Resin: 3.30 – 11.00 $/kg

Combined improvements on part cost HP-RTM floor pan

	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%



Compressed Gas Storage

Compressed Gas Storage Overview

Compressed gas (hydrogen or natural gas) as a cleaner burning fuel is of high interest to vehicle producers and the DOE.

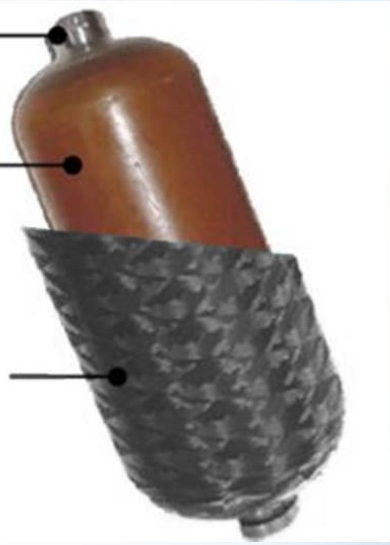
Natural gas has a long history of deployment in passenger cars, fleet vehicles and public buses, using a variety of pressure vessel technologies. The use of hydrogen, particular for fuel cells, is a more recent development, with focus on composite overwrapped pressure vessels.

The lightest weight tanks are based on Type IV pressure vessel designs, featuring a polymeric liner overwrapped with carbon fiber, typically via filament winding. Opportunities for cost reduction may exist in the development of lower cost carbon fibers, faster production methods, or the reduction in safety factors applied to Type IV tanks.

For the baseline, a Type IV onboard hydrogen tank, containing 5.6 kg of H2 at 70 Mpa (700 bar) pressure, was modeled by Strategic Analysis under contract to DOE. Annual volume was assumed to be 130,000 units.

Natural gas tanks in two sizes, one for passenger vehicles (64.4L) and a second for heavy trucks (538L), were also modeled by Strategic Analysis, with sensitivity analyses conducted on fiber price and mass reductions due to reduced safety factors or improved performance.

Onboard 700 bar Type IV H2 Storage System



- Pressure Vessel Component Mass
  - Carbon Fiber: 73 kg
  - Epoxy Resin: 31 kg
  - Plastic Liner: 8 kg
- Capital Eqpt. Investment

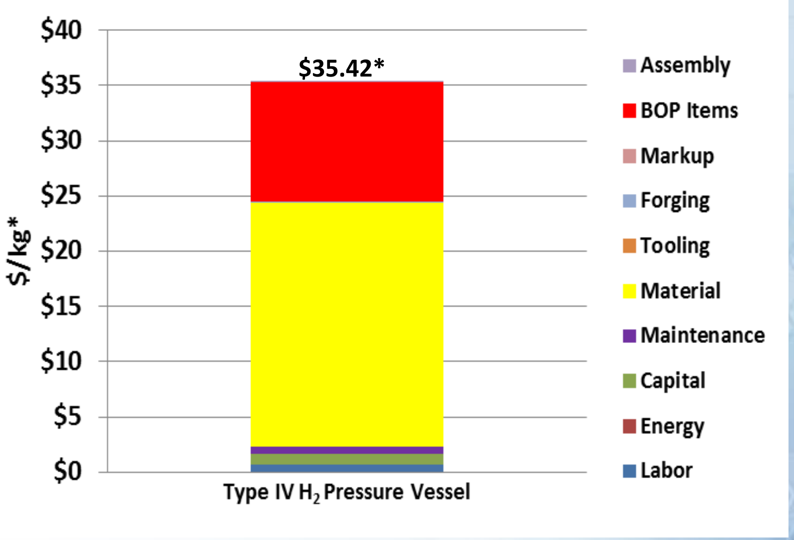
Parameter	Winding	B-Stage Cure	Injection Molding	Full Cure
Capital (per line) $	$400K	$374K	$140K	$744K
Power (per line) kW	15	26	14	147
Machine Life (yrs)	15	15	15	15
Cycle Time (min/tank)	155	5	3.5	3.5

Source: C. Houchins. Personal communication to Sujit Das. SAINC cost model for CFRP pressure vessel, 21 April 2015

Hydrogen Pressure Vessel Cost Analysis

- Cost estimates based on a 70 Mpa, Type IV onboard compressed 5.6 kg usable H_2 pressure vessel for fuel cell vehicle based on filament winding by Strategic Analysis, Inc.
- A detailed cost model consisting of 11 major manufacturing steps using the process-based Design for Manufacture & Assembly methodology of Boothroyd-Dewhurst, Inc.
- Type 4 carbon fiber composite vessel with plastic liner @ carbon fiber $28.66/kg and epoxy resin @$3.63/kg with a plastic liner @$1.76/kg for a production volume of 130K systems/year

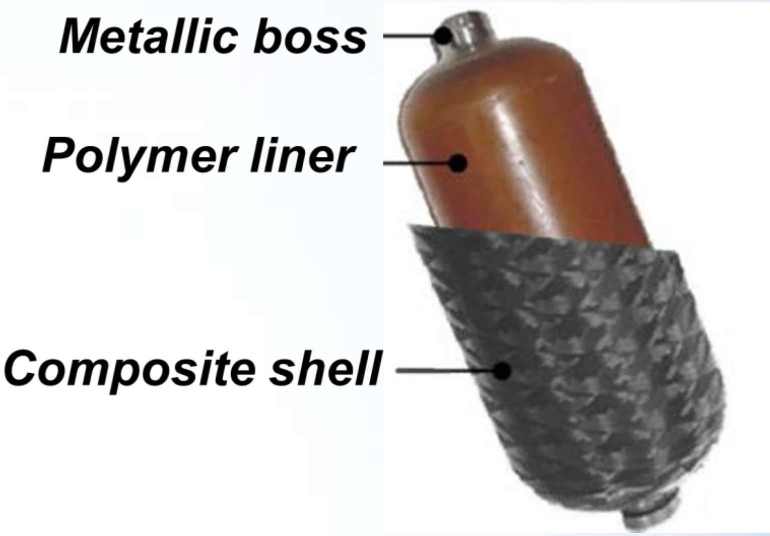
- Material contributes to 62% of total tank cost, of which carbon fiber share is 86.5% -- low cost carbon fiber is one of the major options considered for its economic viability
- Balance-of-Plant (BOP) is another major contributor to tank cost, ~30%
- Other remaining cost components have a less than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



*Estimated based on a composite mass of 104 kg

3600 psi CNG Storage Systems

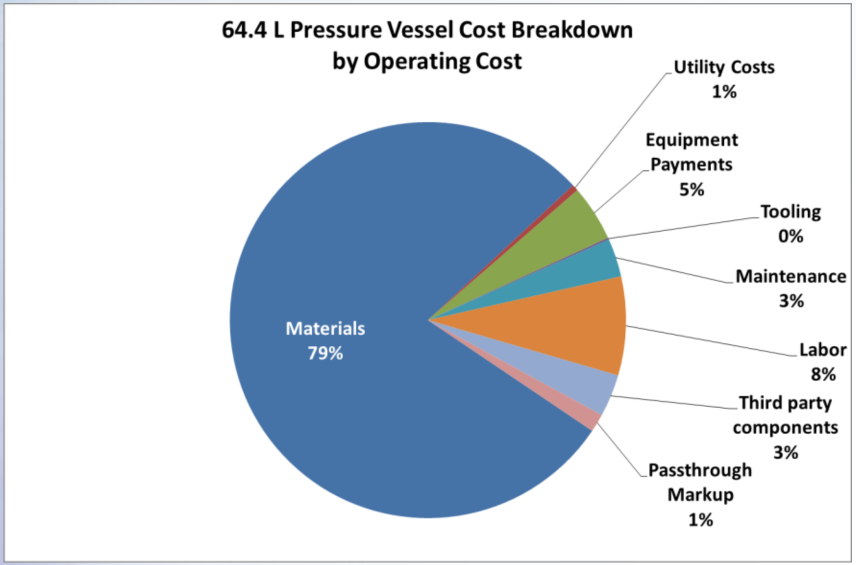
- Two sizes modeled
  - 64.4L liquid volume (passenger cars)
  - 538L liquid volume (heavy trucks)
- Baseline production volumes
  - 64.4L – 500,000 tanks/year
  - 538L – 100,000 tanks/year
- Pressure Vessel Component Mass, 64L
  - Carbon Fiber: 11.1 kg
  - Epoxy Resin: 5.2 kg
  - Plastic Liner: 5 kg
- Pressure Vessel Component Mass, 538L
  - Carbon Fiber: 93 kg
  - Epoxy Resin: 43 kg
  - Plastic Liner: 24 kg



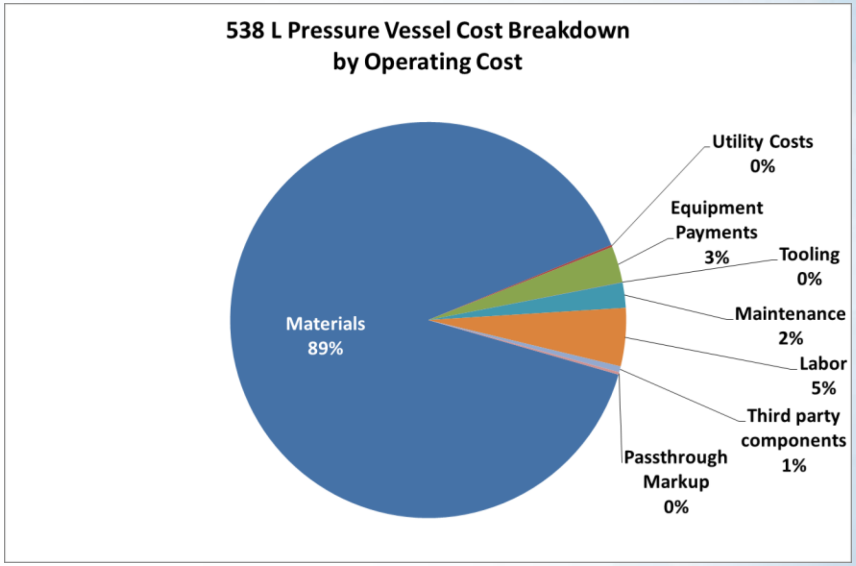
Source: Strategic Analysis, Inc.

Pressure Vessel Cost Breakdown

LDV Vessel



HDV Vessel

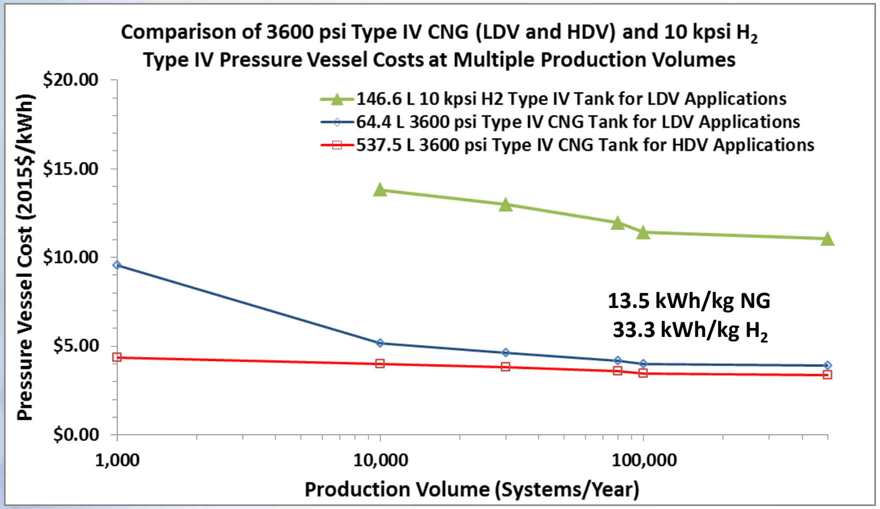


- Costs breakdowns are for pressure vessel only (boss, liner, composite) manufactured at 500k/100k tanks per year
- Utility only includes costs for pressure vessel manufacturer and does not include utility costs for carbon fiber.

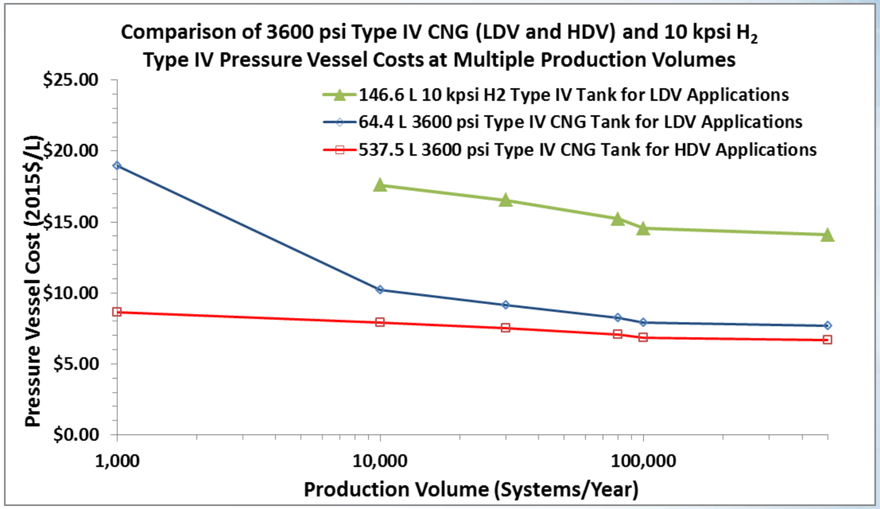
Source: Strategic Analysis, Inc.

Comparison of CNG and H_2 Pressure Vessel Costs

Normalized to Fuel Energy Content



Normalized to Internal Water Volume



- Composite cost for H_2 pressure vessel is based on vinyl ester resin and lower cost PAN-MA carbon fiber as described in the 2015 FCTO Program Record*
- Composite cost for the CNG systems is based on epoxy resin and Toray T700S

*https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

Source: Strategic Analysis, Inc.

CNG Cost Sensitivity Analysis

- 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.

Cost and Energy 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)

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

Conclusions and Future Work

The initial baseline costs and embodied energy will serve as a "starting point" for comparing technology and material or equipment cost improvements and their effect on total part costs and energy consumption. They are not meant to represent the full spectrum of composite components, possible materials, or possible manufacturing processes, but are representative of current practice and market interest.

Within the wind turbine industry, blade costs represent a significant capital expense. Reductions in manufacturing time and carbon fiber costs are expected to translate to blade costs sufficiently lower to increase market penetration.

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 smaller parts. Initial calculations have assumed all scrap is not reprocessed of recycled. This practice is expected to change and have a positive effect on part costs going forward.

Conclusions and Future Work, cont'd

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 is 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.

Further, the methodology used herein to derive the baseline values will be applied, as appropriate, to additional applications and relevant advanced composite markets.

Energy Metrics References

- Carbon Fiber (1155 MJ/kg)
  - 1. S. Das, "Evaluating LCA for Virgin vs. Recycled Carbon Fibre Composites – Focus Areas and Development Opportunities, paper presented at the Go CarbonFibre 2015 Recycling Conference, held on Oct. 29,'15, Manchester, United Kingdom
- Glass Fiber (50 MJ/kg)
  - 2. Ecoinvent LCI Data, SimaPro 7 LCA Software, Version 7.3.3.
- Intermediate Step
  - Dry Weave (36 MJ/kg) (Calculated)
    - 3. ChongKin Yuan Precision Machinery Co., "2014 CKY-845DD High Speed Sofa Belt Weaving Machine Textile Machine Power Loom," 2015. [Online]. Available: http://fjzjy.en.alibaba.com/product/738403244-212352332/2014_CKY_8_45DD_High_Speed_Sofa_Belt_Weaving_Machine_Textile_Machine_Power_Loom.html. [Accessed: 13-Oct-2015].
  - Prepreg (Thermoplastic- 24 MJ/kg (Calculated); Thermoset- 126 MJ/kg)
    - 4. T. Suzuki and J. Takahashi, "Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars," in *Ninth Japan International SAMPE Symposium JISSE-9*, 2005, pp. 14–19.
    - 5 . R. A. Witik, F. Gaille, R. Teuscher, H. Ringwald, V. Michaud, and J. A. E. Månson, "Economic and environmental assessment of alternative production methods for composite aircraft components," *J. Clean. Prod.*, vol. 29–30, no. 3–4, pp. 91–102, 2012.
- Matrix
  - Epoxy (113 MJ/kg) & Polypropylene (76 MJ/kg) (averaged)
    - 6. M. Patel, "Cumulative energy demand (CED) and cumulative CO_2 emissions for products of the organic chemical industry," *Energy*, vol. 28, no. 7, pp. 721–740, 2003.
    - 7. J. G. Vogtländer, *A quick reference guide to LCA data and eco-based materials selection*, First. Ed. Leeghwaterstraat, The Netherlands: VSSD, 2011.
    - 8. Keoleian, S. Miller, R. De Kleine, A. Fang, and J. Mosley, "Life cycle material data update for GREET Model," 2012.
    - 9. I. Boustead, "Polypropylene (PP)," Eco-profiles and Environmental, Product Declarations of the European Plastics Manufacturers, 2014.
    - 10. I. Boustead, "Liquid epoxy resins," Eco-profiles and Environmental, Product Declarations of the European Plastics Manufacturers, 2015.

Energy Metrics References, cont'd

- Molding
  - Filament Winding (4 MJ/kg)
    - 11. C. Houchins. Personal communication to Sujit Das. SAINC cost model for CFRP pressure vessel, 21 April 2015
  - Vacuum Assisted Resin Transfer Molding (4 MJ/kg)
    - 12. Das, S. et al. (2016). "Clean Energy Manufacturing Analysis Center (CEMAC): 2015 Research Highlights,"NREL/BR-6A50-65312| ORNL/SR-2016/98, March.
  - Compression Molding (27.7 MJ/kg)
    - 13. S. Das, "Life cycle assessment of carbon fiber-reinforced polymer composites," *Int. J. Life Cycle Assess.*, vol. 16, no. 3, pp. 268–282, 2011.
  - HPRTM (60.3 MJ/kg)
    - 14. T. Suzuki and J. Takahashi, "Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars," in *Ninth Japan International SAMPE Symposium JISSE-9*, 2005, pp. 14–19.
  - Overmolding
    - 15. Compression Molding (27.7 MJ/kg)
    - Injection Molding (11.0 MJ/kg)
      - 16. A. Thiriez, "An environmental analysis of injection molding by," Massachusetts Institute of Technology, 2006.

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