FRPC Manufacturing
Energy Use Estimator

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Fiber Reinforced Polymer Composite (FRPC) Energy Estimator allows to examine any new IACMI composite manufacturing pathways towards achieving its 50%/75% technical embodied manufacturing energy reduction goal.

**Embodied Energy** is the energy consumed by all of the processes associated with the production of a product, from the mining and processing of natural resources to manufacturing, transport, and product delivery.

Electricity Embodied Energy = 3x Onsite Energy Consumption (kWh)

Manufacturing Energy Savings = $ Part Cost Savings

Annual 1500 t Carbon Fiber Manufacturing Facility 10% Energy Savings = $0.7M*
Energy Estimator Tool Goals

- Calculate fiber reinforced polymer composite (FRPC) embodied part manufacturing energy by major process step
  - **Materials**: Fiber, Matrix, Inserts/Cores
  - **Manufacturing**: Intermediate Processing, Molding, Curing, Finishing

- Identify the most energy-intensive FRPC manufacturing process step
  - Compare energy use between different production processes

- Final FRPC part characteristics guidance for the molding technology selection available for analysis

- Energy intensity of alternative FRPC part manufacturing pathways can be estimated with the user-input data

- Open Source Code and User-Friendly Interface
Model Scope

Several available **Technology Options** for each of the **Seven Major Process Steps**

Allows users to examine **Total FRPC Part Embodied Manufacturing Energy** using

**Different Pathways**
Materials Options

- Fiber Precursor Materials
  - Commodity Carbon Fiber PAN (24K, 50K)
  - Glass Fiber
  - Natural Fiber

- Intermediate Fiber Configuration
  - Prepreg (Hand/Fiber/Tape)
  - Chopped
  - Sheet Molding Compound
  - Powder P4
  - Dry Knit
  - Dry Weave
  - Dry Braid

- Thermosets
  - Epoxy, PS, PU, etc.

- Thermoplastics
  - PP, Nylon, PEEK, etc.

- Fillers

- Additives

- Inserts (for overmolding)
  - Metal
  - Composites
  - Plastics/Foams

Embodied energy data gathered from LCA literature and machinery specifications.
Conventional Molding Processes

• Manual Layup
  – Wet Lay up (open)
  – Spray up (open)
  – Vacuum Bag/Autoclave Molding (closed)

• Shape Specific
  – Pultrusion
  – Filament Winding

Embodied energy data gathered from LCA literature
Newer Molding Processes

- Automated
  - Automatic Tape Placement
  - Automatic Fiber Placement

- Closed Molds
  - Compression Molding
    - SMC molding
    - Thermohydroforming
  - RTM
    - VARTM/SCRIMP
    - HP-RTM
  - Injection Molding
    - Structural Reaction Injection Molding

Embodied energy data gathered from LCA literature, personal conversations, and machinery specifications
Curing & Finishing

- Autoclave Curing
- Out of Autoclave Curing
  - In-mold
  - Oven
  - Microwave
  - Quickstep
  - Infrared
  - Direct Induction
  - Electron Beam

Finishing
- None
- Low – High
  - Rough Estimates Only

Embodied energy data gathered from LCA literature, personal conversations and machinery specifications

FRPC Energy Estimator Tool -- Software

• Open Source:
  – “denoting software for which the original source code is made freely available and may be redistributed and modified”
  – Tool code is available on Github
    • Others can download and run themselves or suggest modifications directly to the code
    • Easily track changes to code
  – Program to run/modify code is also freely available at r-project.org and Rstudio.com

• Temporarily housed and hosted on the Shinyapps.io server
FRPC Energy Estimator Tool -- Framework

• Visually appealing/intuitive
  – Less blocky, more fluid

• More fields can be filled automatically and still be adjusted by user
  – Fewer “overrides” needed
  – Example: matrix mass fraction $f_{matrix} = 1 - f_{fiber}$

• Can hide optional fields
  – Additional matrix materials & inserts

• Online tool: no downloads required
  – Can also download tool from Github for offline use
  – Can download Results, Session Inputs, and Other files from Tool
  – Can upload previous session results
FRPC Energy Estimator Tool – User-Defined

• Allows estimation of energy impacts of user-input alternative manufacturing technology pathways
  – Ability to add technology specific custom energy data (MJ/kg)
    • For all process components (fiber, matrix materials, inserts/cores, fiber intermediate, molding, curing, and finishing)
  – Estimate specific energy for molding and curing from process unit information:
    Rated Power, % Rated Power, Running time, and Weight
    • Vacuum Motor
    • Pump
    • Compressor
    • Process Heating
      – Discrete power vs. time input option to simulate a heating profile curve
    • Other

New Technology Pathways Can be Added to the Technology Database
# FRPC Energy Estimator Tool -- Design

<table>
<thead>
<tr>
<th>TOOL SCREEN</th>
<th>CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Guide" /></td>
<td>Instructions, Load an Example Scenario, Download Tool Documentation*</td>
</tr>
<tr>
<td><img src="image" alt="Upload" /></td>
<td>Upload Custom Data, and Technology Set 1 &amp; 2 Data</td>
</tr>
<tr>
<td><img src="image" alt="Custom Data" /></td>
<td>Input Custom Data by Nine Specific Processing Steps</td>
</tr>
<tr>
<td><img src="image" alt="Initial Inputs" /></td>
<td>Part Name &amp; Weight, Molding Process and Inserts or Core Use?</td>
</tr>
<tr>
<td><img src="image" alt="Fiber" /></td>
<td>Fiber Type and Mass Fraction</td>
</tr>
<tr>
<td><img src="image" alt="Matrix" /></td>
<td>Matrix Type (=1 or &gt; 1) &amp; Mass Fraction</td>
</tr>
<tr>
<td><img src="image" alt="Intermediate" /></td>
<td>Intermediate Type, Scrap Rate, &amp; Recycle Fraction</td>
</tr>
<tr>
<td><img src="image" alt="Molding" /></td>
<td>Molding Yield, Recycle Fraction, Curing Process, Finishing Level (Scrap Rate &amp; Recycle Fraction)</td>
</tr>
<tr>
<td><img src="image" alt="Summary" /></td>
<td>Summary of Selected Technology Data for Technology Set 1 &amp; 2</td>
</tr>
<tr>
<td><img src="image" alt="Results" /></td>
<td>Results in Bar, Pie, and Table formats by Major Processing Steps</td>
</tr>
<tr>
<td><img src="image" alt="Downloads" /></td>
<td>Save Files (Results, Custom Data, Input Files, &amp; Calculations), for Future Upload/Use</td>
</tr>
<tr>
<td><img src="image" alt="Molding Properties" /></td>
<td>Molding Technology Characteristics for its Selection Guidance</td>
</tr>
<tr>
<td><img src="image" alt="References" /></td>
<td>Citations for Available Technology Embodied Energy Estimates</td>
</tr>
</tbody>
</table>

*Tool Documentation Zip file contains Tool User Manual, Energy Data, References, and FRPC baseline metrics analysis case studies
Dropdown menus to choose technology pathways
• Options and data based on literature review
• Does not save to tool’s server
  – Can download file with data for future uploads
### Custom Data

**What type of custom data would you like to add?**

- Molding Process

### Custom Molding Process

Normally the options available for fiber intermediate and curing process are dependent on the user’s choice for molding process. If a custom molding process has been added and chosen, all intermediate and curing process options will be available.

**Name**: Custom Molding Tech

**Is the Specific Embodied Energy of the molding process known?**

**Calculated Embodied Energy**: 0 MJ/kg

### Specific Embodied Energy Calculator

If the specific energy of the molding process is unknown, it can be estimated using the rated power of the equipment involved in the molding process. If multiple pieces of equipment are used, multiply the rated power of the equipment by the fraction of the rated power (i.e., the power used) and enter the sum into the Rated Equipment Power (kW) input and leave the 'Percent of Rated Power (%)' at 100.

**Mass of object molded (kg)**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Rated Power (kW)</th>
<th>Percent of Rated Power (%)</th>
<th>Motor Running Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Motor</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Pump</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Compressor</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Process Heating</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Can add custom data points for each process step and material type**
- **Does not save to tool’s server**
  - Can download file with data for future uploads
Tool Overview - Results

FRPC Energy Use Estimation Tool

- Results as tables, graph, and downloads
- Calculation tables also available for download
Tool Outline and Walkthrough

• The following slides utilize animations to illustrate how to use the tool.
• Watching in presenter mode is recommended.
• Tool is available at:
  https://ornlenergyestimatortools.shinyapps.io/frpc-energy-estimator2/
Example Scenario fills in “Technology Set 1” with one of the tool’s case studies

Tool Documentation includes: user manual, energy data, references, and case studies

Guide also provides tips for using the tool
Custom Data

What type of custom data would you like to add?

- Multiple custom data points can be added for each process segment.
- If the same name is used for different custom energy values, the last added will be used by the tool. This can also be used to temporarily override the energy values for data already in the provided datasets.
- Download the .csv file with all of the custom data from this session to save time in a future session.
- If you wish to directly edit the available data, download R studio and a copy of this app from GitHub.

Click here to view this app on GitHub

Alternatively, contact Kristina Armstrong (armstrongk@ornl.gov) or Sujit Das (dass@ornl.gov), and we can work with you to add your technology to our tool and grow our database of composite manufacturing technologies.

- Can add multiple custom materials/processes per category
- **Does not save between sessions**
  - Can download session custom data for future upload (Download page)
- Can email to permanently add data (for public use) or suggest changes
- Can download tool or suggest changes at GitHub
Can calculate specific energy for molding and curing processes, given equipment specifications.
Choose name, weight, & insert weight
Choose molding early: intermediate & curing are dependent
Red error text until molding technology is chosen
Choose **Fiber Type & Tow**

**Default Fiber Mass Fraction** is determined by Molding technology

Recap section at top reminds user of data entered in previous pages
Choose matrix materials (resin, filler, additive & inserts) and composition

Default Primary Matrix Mass Fraction is 1 – Fiber Mass Fraction

Additional Materials and Inserts entries are hidden until checkboxes are checked

Matrix Tab

Choose matrix materials (resin, filler, additive & inserts) and composition

Default Primary Matrix Mass Fraction is 1 – Fiber Mass Fraction

Additional Materials and Inserts entries are hidden until checkboxes are checked
Fiber Intermediate Manufacturing & Layup

### Technology Set 1

<table>
<thead>
<tr>
<th>Part</th>
<th>Fiber: Commodity PAN, 24k Tow</th>
<th>Fiber: Commodity PAN, 24k Tow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber: Commodity PAN, 24k Tow</td>
<td>1944 kg</td>
<td>30 %</td>
</tr>
<tr>
<td>Matrix: TP Polyethylene</td>
<td>70 %</td>
<td></td>
</tr>
<tr>
<td>Molding Technology: Injection Molding</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Intermediate Tab**

- Choose Intermediate material & layup scrap/recycle rate
- **Default Scrap Rate** is determined by the type of fiber intermediate
- **Recycle Rate** is the fraction of scrap that can be recycled

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**Embodied Energy:**

Choose Intermediate Technology Scrap cannot be negative Scrap cannot be greater than 100%

Default Layup Scrap Rate: NA %

Layup Scrap Rate (%)

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**Embodied Energy:**

Choose Intermediate Technology Scrap cannot be negative Scrap cannot be greater than 100%

Default Layup Scrap Rate: NA %

Layup Scrap Rate (%)

---

---

**Embodied Energy:**

Choose Intermediate Technology Scrap cannot be negative Scrap cannot be greater than 100%

Default Layup Scrap Rate: NA %

Layup Scrap Rate (%)

---

---

**Embodied Energy:**

Choose Intermediate Technology Scrap cannot be negative Scrap cannot be greater than 100%

Default Layup Scrap Rate: NA %

Layup Scrap Rate (%)

---

---

**Embodied Energy:**

Choose Intermediate Technology Scrap cannot be negative Scrap cannot be greater than 100%

Default Layup Scrap Rate: NA %

Layup Scrap Rate (%)

---
Choose molding yield, curing technology and finish level & scrap

Default Molding Yield & Curing Process options determined by Molding technology
**Summary**

**Technology Set 1**

<table>
<thead>
<tr>
<th>Material</th>
<th>Choice</th>
<th>Effective Mass Fraction</th>
<th>Embodied Energy (MJ/part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Commodity PAN, 24k Tow</td>
<td>22.81</td>
<td>561.05</td>
</tr>
<tr>
<td>Primary Matrix</td>
<td>TP Polypropylene</td>
<td>53.22</td>
<td>85.10</td>
</tr>
<tr>
<td>Additional Matrix Material</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Additional Matrix Material</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Additional Matrix Material</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Insert</td>
<td>CFRP - Insert</td>
<td>23.97</td>
<td>507.32</td>
</tr>
<tr>
<td>Insert</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Materials Total</td>
<td></td>
<td>100.00</td>
<td>1153.47</td>
</tr>
</tbody>
</table>

**Technology Set 2**

<table>
<thead>
<tr>
<th>Material</th>
<th>Choice</th>
<th>Effective Mass Fraction</th>
<th>Embodied Energy (MJ/part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>E-Glass Fiber</td>
<td>21.93</td>
<td>26.47</td>
</tr>
<tr>
<td>Primary Matrix</td>
<td>TP Polypropylene</td>
<td>51.18</td>
<td>93.63</td>
</tr>
<tr>
<td>Additional Matrix Material</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Additional Matrix Material</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Additional Matrix Material</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Insert</td>
<td>GFRP - Insert</td>
<td>26.89</td>
<td>59.80</td>
</tr>
<tr>
<td>Insert</td>
<td>Not Used</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Materials Total</td>
<td></td>
<td>100.00</td>
<td>179.89</td>
</tr>
</tbody>
</table>

Review Choices: process step/materials, embodied energy, mass fractions & process scrap/yield
• Compare two technology pathways & save graphs
  – Bar & Pie Charts
  – Energy & percent change grouped by process segment
Download the results, inputs, and the tables used for calculations — .csv & .zip
Can upload custom data and inputs from previous runs to save time
View all the physical and process characteristics of **Molding** technologies in one chart.

<table>
<thead>
<tr>
<th>Molding Processes Visible:</th>
<th>Surface Finish</th>
<th>Part Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic Fiber Placement (AFP)</td>
<td>Fair, One Side</td>
<td>Medium - Large</td>
</tr>
<tr>
<td>Automatic Tape Placement (ATP)</td>
<td>Fair, One Side</td>
<td>Medium - Large</td>
</tr>
<tr>
<td>Compression Molding</td>
<td>Fair, All Sides</td>
<td>Small - Medium</td>
</tr>
</tbody>
</table>
References

To view citations for process and material embodied energy, choose Type and then the specific process/material.

Type

- Select Type

Process/Material

- Select Process/Material

- Quick lookup for data references used in the tool
  - Also available in the background information download
Summary

• Embodied energy intensity of composite part manufacturing can be evaluated for several technology pathways by major manufacturing steps.

• Energy use disaggregated up to three levels:
  – Individual Material Component
  – Major Production Step
  – Overall Production

• Qualitative final part characteristics for each molding options available as a guidance for manufacturing pathway selection for energy use analysis.

• Alternative FRPC part manufacturing pathways can be evaluated with the data availability.

• Comparison allows user to estimate impacts of changes to manufacturing processes.

• Online, open source, user-friendly tool developed:
  https://ornlenergyestimatortools.shinyapps.io/frpc-energy-estimator2/