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TITLE:

From Process Flows to Life Cycle Inventories: Why Energy and Mass Flow Inventories Are Essential for Credible LCA of Composite Manufacturing.

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ABSTRACT:

The World Commission on Environment and Development (WCED) report Our Common Future [1] introduced the concept of sustainability as a necessary consideration for the future of mankind on planet Earth. Sustainability is often defined as a requirement for a balance of economy/prosperity, environment/planet, equity/people or a sub-set thereof. Given that Our Common Future also included governance, and in the technological sphere there is a need for the system to achieve optimal performance, we have previously defined sustainability as a balance of technical, economic, environmental, social, and governance (TEESG) issues [2], and subsequently introduced the Sustainability pentagon (Figure 1).

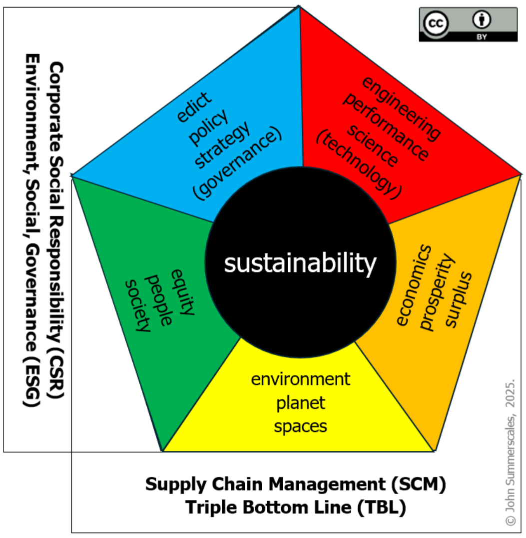

Figure 1: The sustainability pentagon brings together various definitions.

The key methodology for the consideration of the environmental burdens/impacts imposed by any material or process is Life Cycle Assessment (LCA) [3] governed by International Standards ISO14040/14044 [4, 5] and supported by specific guidance framework to support sustainable product policies and fair comparisons of environmental impacts of products/services (i.e. International Reference Life Cycle Data System (ILCD)). A key element of a successful LCA is the Life Cycle Inventory (LCI) data quality [7]. The accuracy of LCA results is particularly dependent on the completeness and reliability of datasets representative of the product flow under assessment. This requirement is typically addressed through the use of primary data and validated via mass and energy balance checks and the analysis of associated process flows.

A close examination of the literature reveals that a large share of composite LCA case studies lacks systematic LCI completeness checks [7], which could be explained by the complexity of process flow in composite manufacturing, particularly at early design stages where process selection and parameter definition remain uncertain. Such gaps potentially contribute to the substantial variability observed across published LCA results for composite products and materials, as illustrated in Figure 2, raising questions regarding the robustness of conclusions drawn for composite environmental sustainability.

The abstract should (a) address **at least one of the core themes**, (b) not exceed two A4 pages of text, and (c) not exceed two further sides of A4 for Figures/Tables

This variability also highlights the need to identify routes to more relevant and accurate information that can be integrated into composite design and manufacturing process to improve the reliability of LCI datasets. In response, this paper discusses flagged sources of variability reported in the current state-of-the-art for LCA of composites, with specific attention to the manufacturing process energy demand (Table 1).

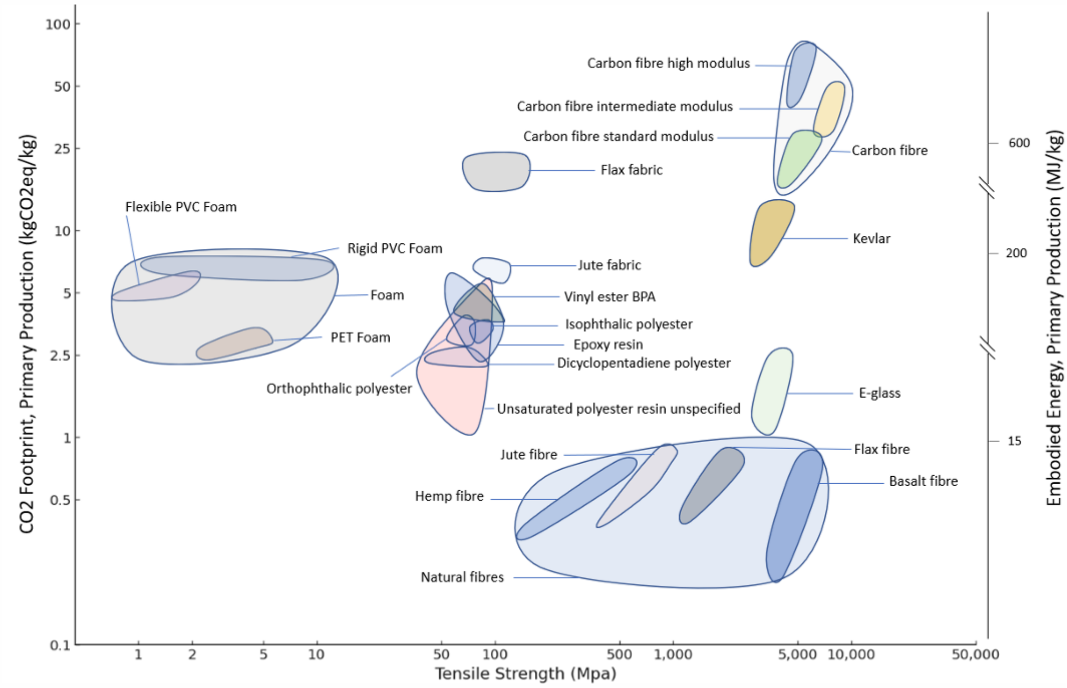

Figure 1.

Review of the literature shows frequent use of inappropriate proxies when specific materials are not in the standard inventory databases. Published works include cases where epoxy base resin is modelled without the hardener, or where textile reinforcement fabrics are modelled without spinning and weaving. While sometimes unavoidable, incomplete accounting of manufacturing energy and material flows generates major uncertainty especially where those losses are poorly documented, thereby widening the spread of reported LCA values for composites.

Composite manufacturing is inherently flow-controlled across processing routes (Table 1), and inventories therefore depend not only on fibre and polymer type, but on the process conditions required to achieve part quality. Energy demand is largely driven by the need to control temperature, pressure, and time, while relevant mass flows extend beyond the part itself to include consumables, resin losses, trimming waste, and rejected parts often underrepresented in LCIs. Consequently, energy and mass flow analysis is essential to produce LCIs that are comparable and representative, particularly in early-stage design where data are sparse. Embedding such flow-based accounting shifts LCA from assumption-sensitive results to traceable, measurable inventories, improving hotspot identification and enabling actionable process improvements (e.g., reduced losses, improved yield, lower energy use).

Table 1: Unit energies for composites processing [8-12]

Process	**Process energy (MJ/kg)**	**Source**
Textile processes		
Open-end yarn spinning	9	Koç and Kaplan [13]
Ring yarn spinning	13	Koç and Kaplan [13]
Electrical energy for woven fabric	8-20	Tarakçıoğlu [14] via [15]
Electrical energy for woven fabric	18	Koç and Çinçik [15]
Electrical energy for woven fabric	21	Visvanathan et al [16] via [15]
Weaving New Zealand merino wool	6-8	Anonymous [17]
Air-jet loom (6-7 MJ/m for 340 mm wide)	~~	Shripal [18]
Composites manufacture		
Autoclave moulding	21.9	Song et al [9]
Autoclave moulding	22.3/66.8	DACOMAT [8]
Cold press	11.8	Suzuki and Takahashi [19]
Cold press	11.8/35.4	DACOMAT [8]
Compression moulding	7.2-15.9	Das [20]
Compression moulding	11.4/34.3	DACOMAT [8]
Glass fabric manufacturing	2.6	Stiller [21]
Filament winding	2.7	Suzuki and Takahashi [19]
Filament winding	2.7/8.1	DACOMAT [8]
Hand lay-up	19.2/57.7	DACOMAT [8]
Infrared oven heating	5.20	Lacoma et al [22] based on 590 g carbon/PPS part
Injection moulding (all-electric)	1.6-3.5	Hesser et al [23]
Injection moulding (hydraulic)	19.0-29.9	Thiriez [24]. Thiriez and Gutowski [25]
Injection moulding	11.2/33.7	DACOMAT [8]
Machining	0.22	Lacoma et al [22] based on 590 g carbon/PPS part
Preform cutting by abrasive water jet	1.55	Lacoma et al [22] based on 590 g carbon/PPS part
Preform matched die	10.1	Suzuki and Takahashi [19]
Preform matched die	10.1	DACOMAT [8]
Prepreg production	40.0	Suzuki and Takahashi [19]
Prepreg	40.0/120.1	DACOMAT [8]
Pultrusion	3.1	Suzuki and Takahashi [19]
Pultrusion	3.1/9.3	DACOMAT [8]
Robot arm handling	0.14	Lacoma et al [22] based on 590 g carbon/PPS part
Sheet moulding compound	3.5-3.8	Suzuki and Takahashi [19]. Das [26]
Sheet moulding compound	3.5/10.5	DACOMAT [8]
Spray up	14.9	Suzuki and Takahashi [19]
Spray up	14.9/44.8	DACOMAT [8]
Stamp forming	9.11	Lacoma et al [22] based on 590 g carbon/PPS part
Liquid composites moulding (LCM) processes		
Resin transfer moulding (RTM)	12.8/38.4	DACOMAT [8]
Resin transfer moulding (RTM) carbon fibre	12.8	Suzuki and Takahashi [19]
Resin transfer moulding (RTM) glass fibre	11.6	Dai et al [27]
Vacuum assisted resin infusion (VARI)	10.2/30.6	DACOMAT [8]
Vacuum assisted resin infusion (VARI)	10.2	Suzuki and Takahashi [19]

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