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GUIDELINES AND RECOMMENDATIONS FOR DATA COLLECTION IN LIFE CYCLE INVENTORY (LCI) FOR COMPOSITES

NILMINI DISSANAYAKE

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Guidelines and recommendations for data collection in Life Cycle Inventory (LCI) for composites

Nilmini Dissanayake
Department of Materials & Mechanical Metrology
Science and Engineering Directorate

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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Approved on behalf of NPLML by
Stefanos Giannis, Science Leader – Advanced Engineering Materials

CONTENTS

GLOSSARY OF ABBREVIATIONS

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
FRP	Fibre-Reinforced Polymer
ISO	International Organisation for standardisation
UN COP	United Nations Conference of the Parties
PAN	Polyacrylonitrile
CE	Cyanate esters
BMI	Bismaleimides
BPA	Bisphenol A
ECH	Epichlorohydrin
CED	Cumulative Energy Demand
MEIT	Ministry of Economy Trade and Industry
JCMA	Japan Carbon Fibre manufacturers Association
EuCIA	European Composites Industry Association

EXECUTIVE SUMMARY

Life Cycle Assessment (LCA) is a tool that can analyse and quantify environmental impacts associated with all stages of a product's life cycle. While there is no legislation in place that requires LCAs to be conducted, there is an increased need and demand for LCA implementation towards achieving net-zero targets in the composite materials sector as well as other sectors and industries. Data quality and lack of specific guidance in conducting data collection specific to composites are significant issues for the development and confidence in using LCA as a decision support tool. The initial scoping study has identified the data quality and measurement gaps that exist within the LCA framework for composite materials. This study aims to provide step-by-step guidance in data collection, interpretation of measurements to Life Cycle Inventory (LCI) data and recommendations in data validation and data recording that can be used in LCI phase to improve data quality and accuracy when conducting a cradle-to-gate LCA study for composites.

INTRODUCTION

The Climate Change Act 2008 commits the UK government by law to reduce greenhouse gas emissions by at least 100% of 1990 levels (net zero) by 2050 [1]. The key arrangements made at the UN climate conference COP26 in 2021 calls on organisations to achieve net-zero emissions, which requires action from organisations to reduce emissions within their supply chain [2]. Life Cycle Assessment (LCA) is a technique that helps the organisations to understand and identify the environmental hotpots within the life cycle of a product or process. The findings from an LCA allow the industry to make environmental strategic decisions in achieving the required reduction in emissions.

LCA evaluates all stages of a product's life from the perspective that they are interrelated (one operation leads to the next). The cumulative environmental impacts resulting from all stages in the product life cycle (e.g., raw material extraction, transportation, manufacturing, disposal etc) can be estimated from LCA which are often not considered in more traditional analyses. LCA provides a comprehensive view of the environmental aspects of a product or process and a more accurate picture of the true environmental trade-offs in product selection by including the impacts throughout the product life cycle.

LCA assess the environmental aspects and potential impacts associated with a product or process or service by [3]:

- compiling an inventory of relevant energy and material inputs and environmental emissions
- evaluating the potential environmental impacts associated with identified inputs and releases
- interpreting the results to make a more informed decision

An LCA framework is provided by international standards ISO 14040 and ISO 14044, which support a consistent approach while allowing the scope and boundaries of the studies to be tailored to a specific situation [4] [5].

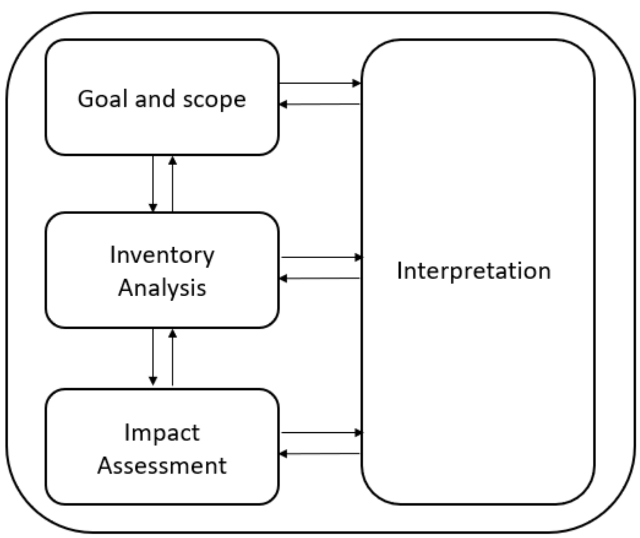


Figure 1 Four phases of Life Cycle Framework [4] [5]

Although the concept of LCA is simple, the analysis is quite complex in reality, primarily due to the difficulty in establishing the correct system boundaries, obtaining accurate data and interpreting the results correctly [6]. Performing an LCA can be resource and time intensive. Gathering data can be problematic and availability of data can greatly impact the accuracy of the final outcomes. Therefore, it is important to use primary data, ideally accurately measured by the LCA practitioner, where possible and assess the quality of data (by validation) used in the LCI.

The data quality gaps and lack of traceability in data used in LCI of Fibre Reinforced Polymer (FRP) composites were previously investigated by researching literature, several interviews with experts and conducting a survey with specific question to LCA practitioners with experience in compiling LCAs for composites [7]. As a follow-on, this study aims to provide guidelines for data collection and interpreting measurement values into LCI data to minimise errors during the primary data collection process and recommendations for data validation and data recording when performing an LCA for composites.

LIFE CYCLE INVENTORY FOR COMPOSITES

LIFE CYCLE INVENTORY

LCI analysis is defined by ISO [4][5] as the “phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle”. All relevant data relates to various environmental inputs and outputs is collected and organised in LCI, and the level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process. LCI analysis requires quantification of elements – energy, raw materials, atmospheric emissions, waterborne emissions, emissions to land, solid wastes and other releases to the environment [8].

The following are the four steps to be followed in an LCI analysis [8]:

1. Development of a flow diagram of the processes within the defined system boundary
2. Development of a data collection methodology
3. Collection of relevant data
4. Evaluation and reporting of the results

Cradle-to-grave study assesses the full life cycle of the product from resource extraction (‘cradle’) to the use phase and disposal phase (‘grave’). Cradle-to-gate is a partial assessment of product life cycle from resource extraction (cradle) to the factory gate (before the user phase).

LCI FOR COMPOSITE PRODUCTION

Fibre-reinforced polymer composites composed of fibre bundles impregnated by a polymeric matrix material. Composite materials are designed and built to combine the properties of their constituents to produce a superior end-product. Fibre-reinforced composites can be manufactured in several different ways depending on the size and orientation of the reinforcement, as well as the type of matrix used.

LCI for cradle-to-gate composite production can be divided in to three main segments as fibre production, resin production and composite manufacturing.

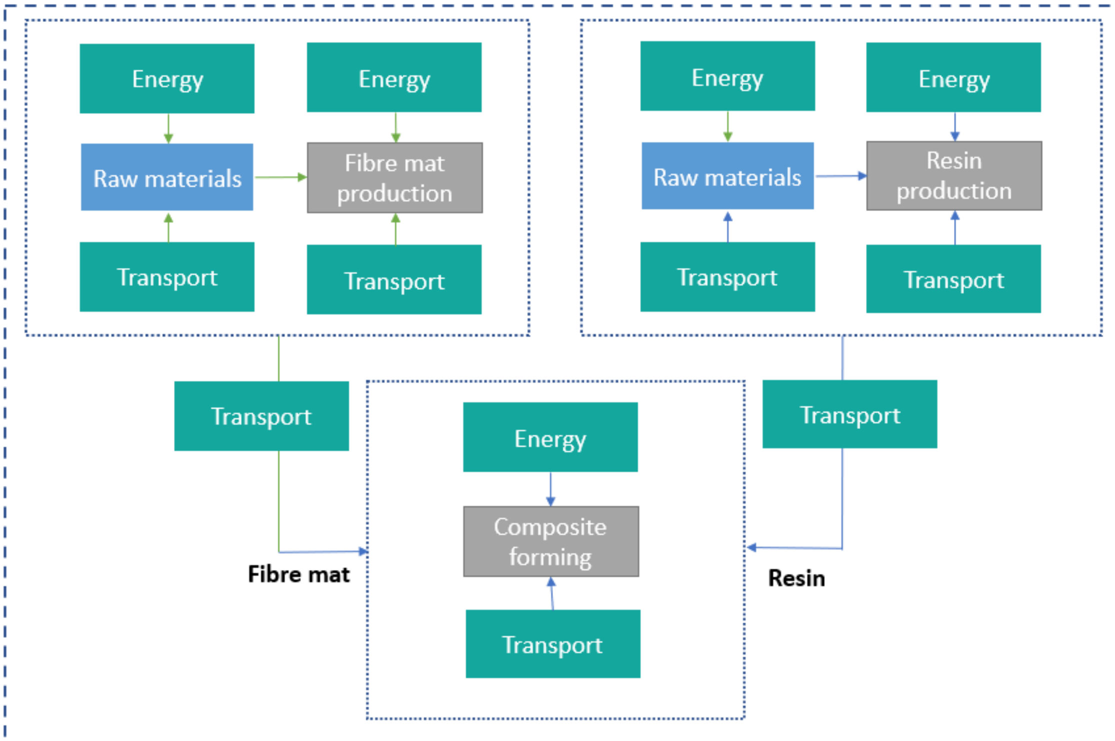


Figure 2 Elements of LCI for cradle-to-gate analysis of composite material production

Figure 2 illustrates the inputs of LCI in terms of energy and transport and emissions to air, water or soil at each production stage should also be included. Ideally, other elements such as production and maintenance of machinery/tools and their end of life, packaging and storage at each stage should be considered within the system boundary of the study to make it complete. Energy consumed in production of ancillary materials e.g., fibre coatings, binders, hardeners used in resin production are usually not included in LCA studies for composites [9] [10] [11] [12] [13] [14]. It was also reported that data availability of production of secondary materials e.g., epoxy hardener is very limited in commercially available databases [15].

Glass fibre production

Glass fibre manufacturing is the high-temperature conversion of various materials into a homogeneous melt, followed by the conversion of this melt into glass fibres. Glass fibres come in a variety of forms although over 95% off all reinforcements are E-glass. There is a number of LCA studies compiled on glass fibre production which include data for flat glass, textile glass fibre and glass wool [11-13] extracted from various sources. Glass fibre production can be segmented into three phases [17]:

i. raw material extraction,
ii. glass melting and refining and
iii. fibre forming and finishing

Typical life cycle of glass fibre production with the elements to be considered in LCI is shown in Figure 3.

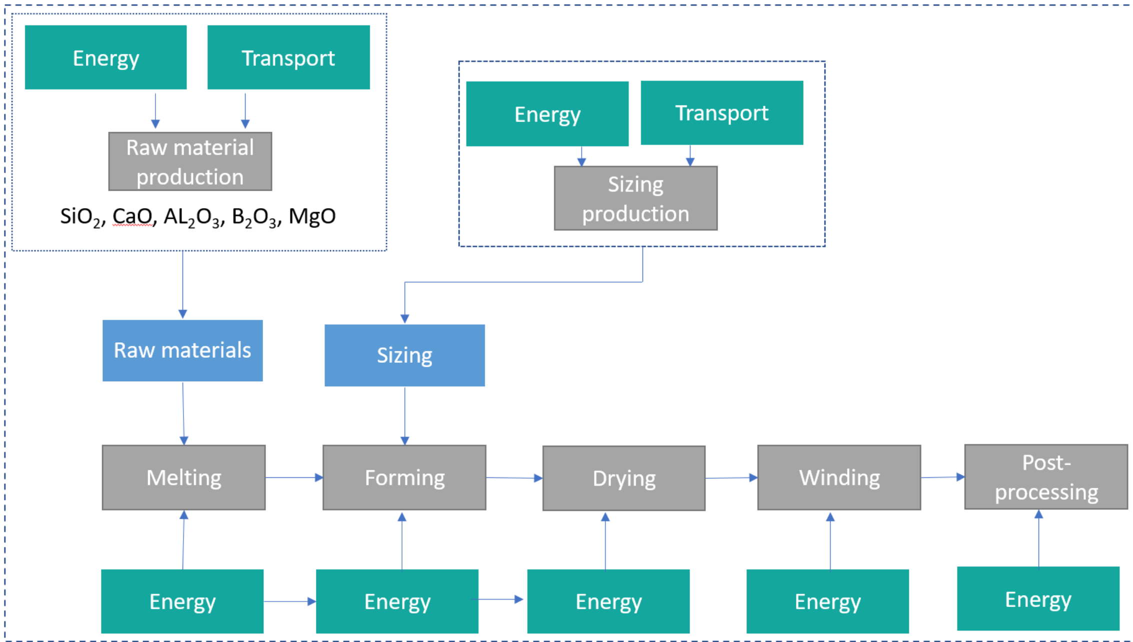


Figure 3 Scope of LCI in glass fibre reinforcement in composites

Glass fibre manufacturing plants usually are located within the proximity of reliable supplies of raw materials other than boric acid which is always imported to the plant. The main forms of energy used are electricity to drive machines, fans, blowers, compressors, conveyors etc. and natural gas to maintain working temperatures. Melting produces large amount source of nitrogen emissions and modern furnaces aim to increase fuel efficiency and reduce emissions. Energy used in forming is highly product dependant and emissions, packaging, storage, machinery production, maintenance and end of life should be considered in LCI.

Carbon fibre production

There are two main manufacturing methods for carbon fibres that have been commercialised, production from a polyacrylonitrile (PAN) precursor and conversion of petroleum precursor. The PAN process is by far the most common method used involving both chemical and mechanical processes. The PAN process was considered as both the current typical and the state-of-the-art manufacturing method for carbon fibres [18].

The following steps are typical in the PAN process for the manufacture of carbon fibre.

i. Spinning – PAN is mixed with other ingredients and spun into fibres which are washed and stretched
ii. Stabilizing – The fibres undergo chemical alteration to stabilize bonding
iii. Oxidation/carbonization – Stabilized fibres are heated to very high temperature forming tightly bonded carbon crystals
iv. Surface treatment – the surface of the fibres is oxidized to improve bonding properties
v. Coating/finishing – fibres are coated with sizing for protection and wound onto bobbins, which are loaded onto spinning machines that twist the fibres into different size yarns.

Typical stages of carbon fibre produced using PAN process are shown in Figure 4 with elements to be considered in LCI.

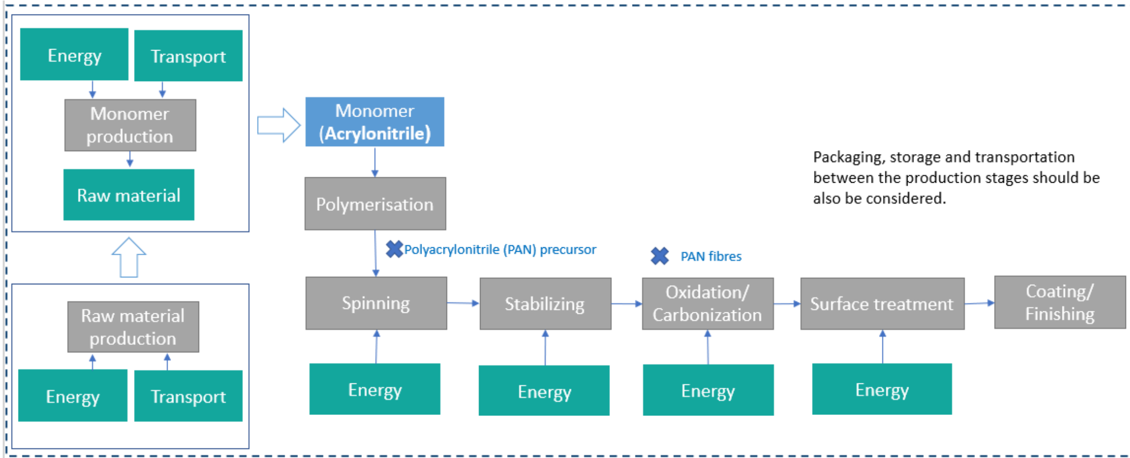


Figure 4 Scope of LCI in carbon fibre production using PAN process

Resin production

The polymers most widely used in composites are thermosets (a class of plastic resins which become substantially infusible and insoluble when cured by thermal and/or chemical by a catalyst or promoter or other means), Unsaturated polyester resins are the most widely used thermosets in commercial, mass production applications due to ease of handling, good balance of mechanical, electrical and chemical properties and low costs. Vinyl ester resins offer a bridge between lower-cost, rapid-curing and easily processed polyesters and higher-performance epoxy resins. Vinyl esters are used in applications such as chemical tanks where corrosion resistance is important. For advanced composite matrices, the most common thermosets are epoxies, phenolics, cyanate esters (CEs), bismaleimides (BMIs), benzoxazines and polyimides [19].

Typical stages of epoxy resin production are shown in Figure 5.

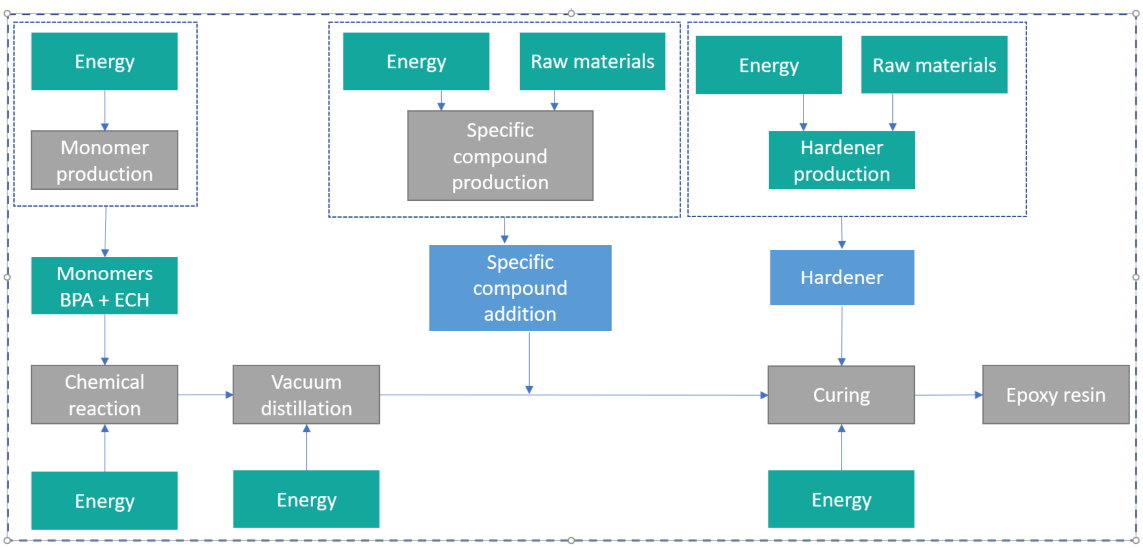


Figure 5 Scope of LCI in epoxy resin production
***(BPA and ECH are the main monomers used in epoxy production)**

Composite forming

Composites are manufactured using many techniques including:

- Wet lay-up
- Spray-up
- Compression moulding
- Injection moulding
- Resin transfer moulding
- Vacuum infusion
- Filament winding
- Pultrusion
- Prepreg

The energy required to operate machinery or equipment should be recorded in the LCI. The production output, waste, machinery production, maintenance and end of life and all associated emission must be included in a comprehensive LCA study. The elements that are included and excluded must be clearly defined by the goal and scope definition and system boundary of the LCA.

DATA ISSUES IN LCI FOR COMPOSITES

Comprehensive LCA studies for composites were searched in the literature to identify the data and measurements gaps that may exist within the LCA framework and to understand the measurement techniques that are used in the primary data collection. The purpose of this was to understand the gaps and subsequently make necessary suggestions to improve primary data collection and secondary data use in the LCI for composites.

However, it has not been possible to identify comprehensive LCA studies for composites to assess the data gaps or measurement techniques. Some of the common observations in searching literature include:

- LCI with primary data did not contain the raw/measured data points for review
- LCI contained a mix of primary data and secondary data with no clear indications
- data were extracted from commercial databases with limited traceability
- no record of measuring techniques
- no record of geographical and technological parameters
- lack of data source and referencing details
- no clear assumptions in calculated data

Therefore, it is useful to find out how the data arrives in LCA studies and where they originate. Any data point in LCI has gone through a sequence of collation, calculation, manipulation activities linking primary or secondary data to LCA results which may vary in length. Some of the data pathways can be more robust and some may include weak steps e.g., calculations vs direct measurements or automatic transfers vs manual transcriptions.

ANALYSIS OF DATA FLOW PATHWAY

The quality of the data used to determine the validity of the whole LCA, and analysis of data flow pathway can be used to trace the data back to the source. This will enable identification of high-risk steps within that pathway and the focus points in data collection/measurement. There is plenty of scope for error within diverse data pathways.

Some common examples for weaker steps on the LCI data flow pathway can include:

- failure to convert units from records on a consistent basis
- mixture of data from different time periods e.g., previous year total flows/run hours applied to current year
- unnoticed mid-year change in energy billing units
- outdated air emissions analysis used with changed material inputs
- transcription errors

Data audit "back to source" is resource-intensive and time-consuming task which is not practical for 100% of the data. Therefore, for this study this task was limited to some data reported for glass and carbon fibre production.

Data reported in glass fibre production

Literature search was undertaken to identify a detailed LCA study for the production of glass fibre reinforced composite material as this was not an easy task, LCA for glass fibre production was chosen to conduct the analysis for data flow pathway.

The report published in 2015 [20] outlines the energy consumption for production of E-glass at each processing stage from various literature sources as in Table 1 below.

Table 1 Energy Consumption for E-glass production from *Dai et al 2015* [20]

Table 3. Energy consumption for E-glass production (MMBtu/ton)

Processing stage	Ruth et al 1997	DOE 2002	Rue *et al* 2007	Worrell *et al* 2008	Scalet *et al 2013*
Batch preparation	1.15*	1.15*	0.68*	1.1*	---
Melting and refining	9.89*	5.6-10.5	6-7	5.6-10.5	6.02-15.48
Forming	7.24*	7.2*	1-2	2-5.5*	---
Post-forming	2.74*	3.28	1-2	3.3	---

*Data representing both textile glass fiber and glass wool production

The first set of data referenced as *Ruth et al 1997* [21] was traced back and found a table which was referenced to the source as *Energetics (1990)* [22] as shown in Table 2. The actual data set was reported from *1985* which cannot be traced any further. The dataset might have been obtained prior to 1985 and meta data could not be identified. This dataset has been used over three decades by many LCA studies and may even got cited after 2015.

Table 2 Table of data from *Ruth et at 1997* [21]

Ecology of the US glass industry: M Ruth and P Dell'Anno

Table 2 Energy use by glass production technologies *Source*: Energetics (1990)

Process	Ton of product/ton finished glass (1985)	Process mix ave annual % change[a]		Million Btu/ton of product (1985)	Energy use, ave annual percentage change[a]	
		State-of-the art (2010)	Advanced (2010)		State-of-the art (2010)	Advanced (2010)
Flat glass						
Batch preparation	1.32	NA	0.19	0.27	0.47	NA
Melting and refining	1.26	NA	0.20	8.10	1.85	3.97
Forming	1.26	NA	0.20	1.45	0.44	0.86
Post-forming	1.20	NA	NA	2.20	1.30	1.92
Container glass						
Batch preparation	1.32	NA	0.25	0.53	0.40	NA
Melting and refining	1.26	NA	0.23	6.34	1.10	2.99
Forming	1.20	NA	0.24	4.01	0.90	1.32
Post-forming	1.13	NA	NA	1.84	1.09	1.30
Fibrous glass						
Batch preparation	1.30	NA	NA	1.15	0.40	NA
Melting and refining	1.24	NA	NA	9.89	0.35	4.31
Forming	1.11	NA	NA	7.24	0.75	1.17
Post-forming	1.00	NA	NA	2.74	0.63	0.84

[a]Assumes exponential decline in efficiency improvements.
NA indicates no change from current to state-of-the-art or advanced technologies.

The second data set for glass fibre production is referenced as *DOE 2002* [23] and data included in this report was compiled from published sources, communication with industrial experts and government reports in the period 1980s-2000. Individual data points are not referenced and there is no record of measurement techniques used in data collection.

The third data set referenced as *Rue et al 2007* [24] has used data from different sources including the *DOE 2002* report. But the values extracted from the report are for "glass wool" production and not glass fibre (Table 3). Other data originate from a survey which cannot be traced any further.

Table 3 Glass fibre production energy use data from *Rue et al 2007* [24]

Table 6: Glass Fiber Production Energy Usage

	Current Average[1,4]				State of the Art[4]		Pr Mi
	Wool		Textile		Wool	Textile	Wool
	(MMBtu/ton)	(%)	(MMBtu/ton)	(%)	(MMBtu/ton)		(MM
Mixing[1]	0.68	6%	0.68	7%	-	-	-
Melting / Refining[4]	4.5	37%	6.5	64%	2.8	3.8	2.3
Forming[4]	5.0	41%	1.5	15%	-	-	-
Post-Forming[4]	2.0	16%	1.5	15%	-	-	-

[1] "Energy and Environmental Profile of the U.S. Glass Industry", Energetics Inc., 2002.
[2] Brown, H. L. et al., "Energy Analysis of 108 Industrial Processes", 1996.
[3] "Integrated Pollution Prevention and Control, Reference Document on Best Available Techniques in the Glass Manufacturing Industry", 2001.
[4] Data obtained by Dr. Warren Wolf from surveys conducted with glass industry representatives.

The fourth data set referenced as *Worrell et al 2008* [25] has used the references Ruth *et al* 1997 and Rue *et al* 2007 in data collection. However, the values used in the table are estimated specific energy consumption for fiberglass, textile fibres and reinforcement fibres as shown in Figure 9 hence they are different to the other data sets.

Table 4. Specific energy consumption for glass production from *Worrell et al 2008* [25]

Table 8. Estimated specific energy consumption of glass forming processes

Industry Segment	Average Specific Energy (MMBtu/ton)		
	Electricity	Electricity Losses[15]	Primary Energy[16]
Flat glass	1.5	3.1	4.6
Container glass	0.4 – 0.7	0.8 – 1.5	1.2 – 2.2
Specialty glass	5.3	11.0	15.3
Fiberglass	2 – 5.5	4 – 11.8	6 – 17.3

Source: U.S. DOE (2002a)

Table 7. Estimated specific energy consumption of glass melting furnaces

Industry Segment/ Furnace Type	Current Estimated Share	Average Specific Energy (MMBtu/ton)[11]			
		Natural Gas	Electricity	Electricity Losses[12]	Primary Energy[13]
Textile/reinforcement Fibers					
Recuperative	25%	10.5 (6.0-15.0)	-	-	*10.5*
Oxy-Fuel	75%	5.6 (3.4-7.8)	-	-	*5.6*

Source: U.S. DOE (2002a); Rue et al. (2006)

Table 6. Specific energy consumption of major process steps by industry segment

Process Step	Average Specific Energy (MMBtu/ton)			
	Flat Glass	Container Glass	Specialty Glass	Fiberglass
Batch preparation	0.3	0.5	0.8	1.1
Melting and refining	6.5	5.8	7.3	5 – 6.5
Forming	1.5	0.4	5.3	1.5 – 4.5
Post-forming/finishing	2.2	0.7	3.0	1 - 2

Source: U.S. DOE (2002a); Rue et al. (2006)

Table 9. Estimated specific energy consumption of post-forming and finishing processes

Industry Segment/Process	Average Specific Energy (MMBtu/ton)			
	Natural Gas/Fuel Oil	Electricity	Electricity Losses[17]	Primary Energy[18]
Flat Glass				
Annealing	0.4	0.01	0.02	0.43
Tempering (gas)	4.0	0.19	0.39	4.58
Tempering (electric)	-	1.85	3.84	5.69
Laminating	1.0	-	-	*1.0*
Autoclave	0.5	0.14	0.29	0.93
Container Glass				
Annealing & finishing	1.6	0.23	0.48	2.31
Specialty Glass				
Annealing & polishing	3.0	0.05	0.10	3.15
Fiberglass				
Glass Wool	4.4	-	-	*4.4*
Textile Fibers	3.3	-	-	*3.3*

Source: U.S. DOE (2002a)

The fifth data set in Table 1, which is referenced to the *Scalet et al 2013* [26] has reported a wide range in values for energy consumption 6.02-15.48 MMBtu/ton for melting and refining in E-glass production. The tables contained in the article, outlines energy consumption in melting and refining glass (not specified as glass fibre) using different types of furnaces. The unit of specific energy consumption used in Table 5 (*Scalet et al 2013* [26]) is KJ/kg and was presented as MMBtu/ton by Dai et al [20] in Table 1. It was not possible to identify the individual data points that were used in Table 1 using the data in Table 5 as the different types of data was presented using different units.

Table 5 Specific energy consumption for a range of glass furnaces from *Scalet et al 2013* [26]

Table 3.8: Examples of specific energy consumption for a range of glass furnaces

Tank furnace type	Glass type	Melting area (1) (m^2)	Glass bath depth melting end (mm)	Tank capacity melting end (t)	Length/width ratio of the tank bath	Output (t/d)	Specific output (t/m^2d)	Specific energy consumption (2) (kJ/kg glass)
Cross-fired furnace with regenerative air preheating	Container glass	15 – 155	1200 – 1700	50 – 500	1.9 – 3.0:1	40 – 500	2.5 – 4.0	4200
Regenerative end-fired furnace	Container glass	15 – 140	1200 – 1700	50 – 500	1.9 – 2.5:1	40 – 450	2.5 – 4.0	3800
Recuperative furnace	Container glass	Up to 250	1100 – 1600	50 – 650	2.0 – 2.8: 1	40 – 450	2.0 – 3.0	5000
Oxy-fuel fired furnace	Container glass	110 – 154	1300 – 1700	390 – 600	2.0 – 2.4:1	350 – 425	2.3 – 3.5	3050 – 3500(3)
Cross-fired furnace with regenerative air preheating	Flat glass	100 – 400	1200 – 1400	300 – 2500	2.1 – 2.8:1	150 – 900	2.3 – 2.7	6300
Cross-fired furnace with regenerative air preheating	Television tube glass (screen)	70 – 300	900 – 1100	160 – 700	2.0 – 3.0:1	100 – 500	1.1 – 1.8	8300
Furnace with recuperative air preheating	Tableware	15 – 60	1100 – 1300	40 – 180	1.8 – 2.2:1	15 – 120	1.0 – 2.0	6700 – 11000(4)
Cross-fired furnace with regenerative air preheating	Tableware	30 – 40	800 – 1000	65 – 100	2.0 – 3.0:1	40 – 60	1.2 – 1.6	8000 – 11000
Regenerative end-fired furnace	Tableware	45 – 70	800 – 1800	100 – 250	1.8 – 2.2:1	120 – 180	2.0 – 3.0	5000 – 6000
Furnace with recuperative air preheating	Glass wool	15 – 110	800 – 1500	50 – 200	2.8:1	30 – 350	3.4	4300 – 6500

(1) Surface area of glass furnace for glass melting and refining; normally the area between the doghouse and the throat; in the case of float glass furnaces, without the unheated conditioning area.
(2) Specific energy consumption without working end and feeder during start-up and nominal load operation (energy consumption will generally increase by 0.1 to 0.2 % per month, due to ageing of the furnace, without electrical boosting, melt preheating and secondary waste heat utilisation) is standardised to:

- 70 % cullet for container glass
- 20 % cullet for float glass
- 40 % cullet for television tube glass and tableware.
- energy savings per cent of additional cullet used: 0.15 to 0.3 %.

The specific energy consumption figures given are approximate guide values for new medium-size and large plants. They are not suitable for energy balance considerations owing to the large differences which occur in individual cases. The effective specific energy consumption is dependent not only on the cullet content and the tank age, but also, '*inter alia*', on batch composition, air preheating, specific tank loading, insulation of the tank and the required glass quality standard.
(3) The data indicated are based on the operating experience with two commercial plants using oxy-fuel technology. The energy required for oxygen production is not included in the specific energy consumption.
(4) The lower range of specific energy consumption for recuperative furnaces may be related to a lower quality standard of the glass produced. In general, regenerative furnaces present lower specific energy consumptions than recuperative furnaces.
Source: [42, VDI 1997] [136, EURIMA 2008] [137, Domestic glass 2008]

BMS/EIPPCB/GLS_Final_Draft March 2012 95

Data reported in carbon fibre production

Similarly, a study with different values for carbon fibre production was identified to analyse the data flow pathway. The article published in 2020 [27] contains a list of data for energy consumption (CED) sourced from literature from 2001-2014 for virgin carbon fibre production as shown in Table 6.

Table 6 CED values from literature for virgin carbon fibre production from *Tapper et al 2020* [27]

Table 1
Table summarising EI, GHG and costs of common CFRP constituents found in the literature.

Material	CED	GHG	Cost
	MJ/kg	kg CO2eq/kg	£/kg
Steel	13-56 [10]		
	25.0–44.6 [48]	2.26-2.49 [48]	0.48-0.58 [49]
Recycled Steel	9.0–52 [10]		
Aluminium	197-298 [50]		
Fibre			
Virgin Carbon	171 [51]		
	183-286 [16,52]	–	–
	353 [53]	–	–
	478 [16,52,54]		
	198-595 [55]	–	–
	771 [56]		
	286-704 [57]	24.4–31.0 [49]	
	–	–	21.2–47.0 [58, 59]
Glass	13.0–54.3 [32,60]	–	–
	45.6 [38]	2.50 [38]	
	48.3 [45]	2.04 [45]	–
			1.59-3.54 [49,58]
Aramid	222-245 [49]	16.4–18.2 [49]	21.2 [9]
Flax	6.50-11.6 [59]	0.45 [59]	1.57-3.14 [49]
Matrix			
Thermoset			
Epoxy	140-144 [45,61]		3.00–15.0 [62]
	76-80 [16,38]		
	76-137 [57]	4.7–8.10 [57]	
Polyester	63-78 [16,63]	2.8-3.10 [16,63]	1.00–2.00 [62]
Thermoplastic			
ABS	95 [45,64]	3.10	1.22
PVC	53-80 [65–67]	2.20 [32]	1.36 [32]
Polypropylene	22.4–112 [16,45, 61]	1.85-2.60 [16,45, 61]	1.23 [49,64]
Nylon	139-145 [61,68]	6.50-8.33 [61,68]	1.66-2.55 [49,64]
PC	80-112 [32,69]	6.00–7.50 [32,69]	1.82 [49,64]
LDPE	65-92 [32,70]	1.80 [67]	1.22 [66]

The references quoted in the table above were searched and traced back as far as possible to identify the source of the data. One of the references [28] can be traced back to a report published in 2004 by the Ministry of Economy Trade and Industry (MEIT) in Japan but cannot traced further back and there is no record of any metadata. Another of the references [29] has extracted the data from Japan Carbon Fibre Manufacturers Association (JCMA) website, which claims to have an inventory of standard grade PAN based carbon fibre data that is reviewed every 5 years based on actual production data of Toray, Toho Tenex and Mitsubishi Rayon [30]. The published information on the website includes overview of LCI data for carbon fibre and the LCA model. The report from The Society of Japanese Aerospace Companies [31] cannot be traced and the report from Boeing [32] does not mention any details on the data collection techniques. EuCIA (European Composites

Industry Association) Eco calculator was also used to arrive at the figures which cannot be traced back to the source.

The issues highlighted from analysing the data flow pathway include the use of very old data with new references, lack of meta data information, traceability, use of different data types with no other information and no record of data collection or measurement techniques.

DATA COLLECTION GUIDELINES

Data collection phase in LCI is one of the most time-consuming, data-intensive and iterative tasks in LCA studies. There are currently no widely recognised guidelines for LCA practitioners for data collection. Lack of guidance is leading to inefficient, non-transparent and inconsistence steps taken in the LCI phase which affects the outcomes of LCA studies. Therefore, it is important to have a step-by-step data collection guidance to eliminate the errors that may aggregate in data collection phase. The lack of harmonization in data reporting and collection makes the LCA studies non-transparent and non-reproducible. Issues reported in this study in data used/recorded for glass fibre and carbon fibre production have highlighted the need for improved transparency and reproducibility in LCA studies for composites production. Guidelines for data collection and measurements will help to bridge the gap between the quality and usefulness of LCA studies as it will enable the reported LCIs to be reused by LCA practitioners for other studies with improved confidence.

PLANNING PHASE

The planning and preparation step initially starts with the first step of LCA framework, goal and scope definition. Data requirements can be defined based on the functional unit and system boundaries chosen for the study. The data requirements can be categorised as inputs and outputs to understand the elements involved in the LCI creating an overview of the whole system to study.

The breaking down of LCI into segments can also be done at the planning stage. The LCI for composite production can be broken down into three main segments as fibre production, resin production and composite forming and each of those segments can be further broken into sub segments such as raw material, processing, transport etc to simplify the data collection as shown in the Figure 6.

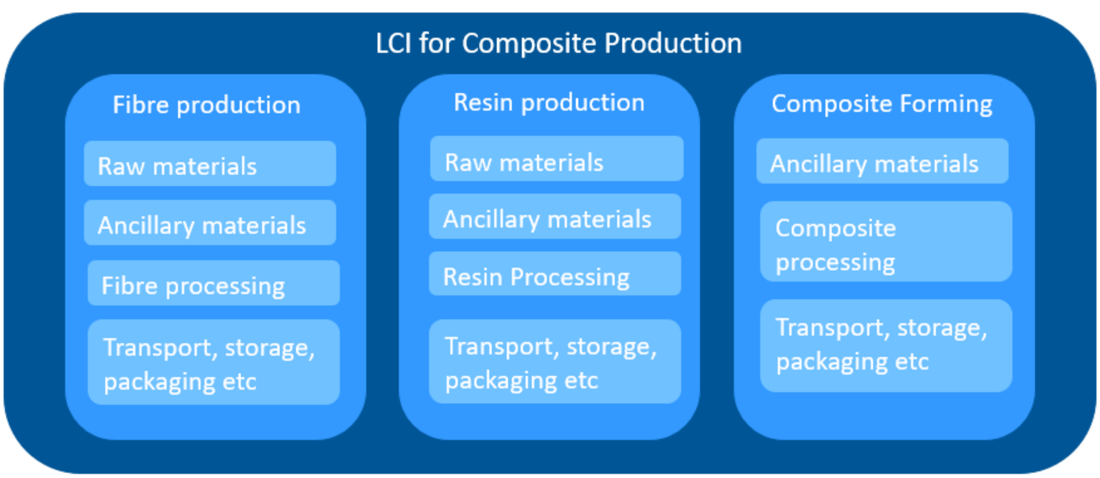


Figure 6 Breakdown of LCI for composite production into segments

LCI breakdown consists of identifying and differentiating subcomponents of the product under study. This can be done by examining the product system very closely. Each segment represents a single or multiple unit process which are interlinked to the main system.

3.1.1 Identification of data requirement

The types of data necessary to build the LCI of the system under the study need to be identified and specified. LCI consists of inputs (e.g., energy, raw materials or water) and outputs (e.g., products, by-products or emissions) generated by a product or system throughout its life cycle. The inputs and outputs are reported in terms of amounts associated with the product (functional unit) which are treated as either intermediate flows (e.g., waste, products or by-products within the technological system) or elementary flows (e.g., emissions to air or extraction of raw materials from the ground which represents flows of material and energy from/to the environment). For each life cycle stage, different LCI data requirements exist. The collected data for the LCI is either primary or secondary data depending on the time and data resources available, and the detail needed in the study to satisfy the goal and scope.

Data requirement for LCI in a cradle-to-gate LCA study for composite manufacturing is illustrated in Figure 7.

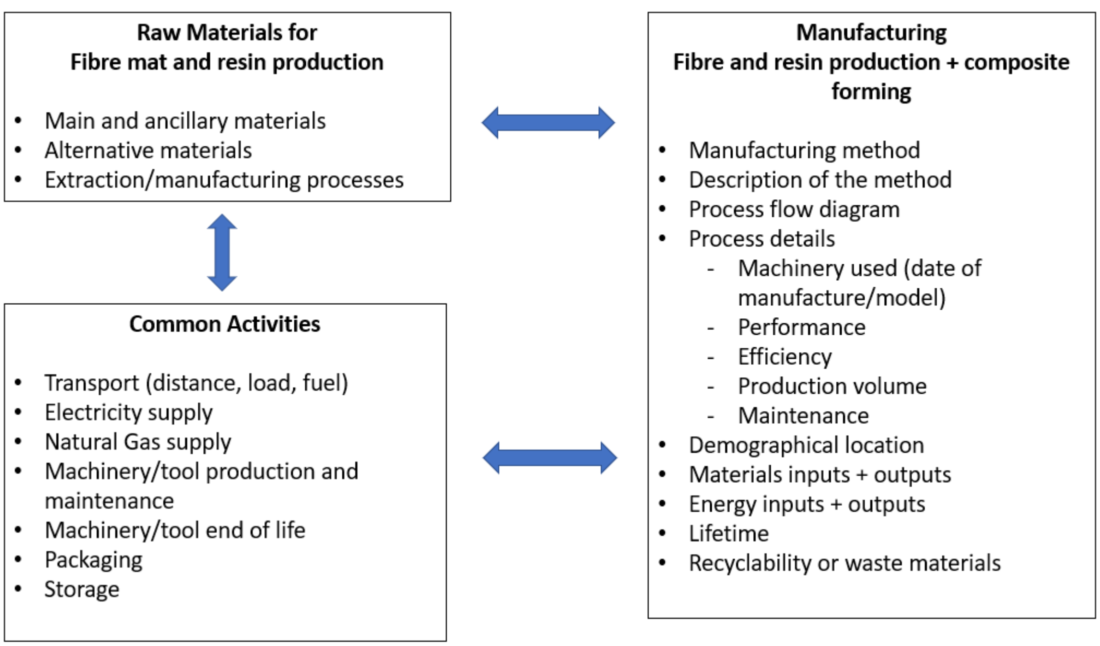


Figure 7 Data requirement for LCI for cradle-to-gate LCA study for composite manufacturing

Raw materials extraction – This covers any extraction or processing activity that raw material may need before being used in the manufacturing of the system of study.

Manufacturing/production stage – This stage involves all the activities required to process raw materials into intermediate products (e.g., fibres and resins) and ultimately into the final product of the study (e.g., composite). The chosen manufacturing method needs to be described by a process flow diagram and specified by its performance, efficiency, production volume, yield and maturity. Inputs and outputs of each manufacturing step needs to be specified. These can be divided into materials (e.g., raw materials and auxiliaries) and energy (e.g., electricity, natural gas). The main products, by-products and emissions can be classed as outputs. Additional data requirements for the manufacturing stage are the lifetime of the final product and recyclability depending on the scope of the chosen study.

Common activities – The activities correspond to all other activities that could occur within each of the life cycle stages or in between can be considered as auxiliaries or common activities. These include transport, energy supply, maintenance, storage, packaging etc. As an example, data requirements for transport activities are the mode of transport (e.g., via sea, road, rail or combination of all), the means of transportation used (e.g., railway, barge, truck, pipeline, transmission lines or combination), including specification regarding amount and type of fuel (e.g., petrol, diesel or gas), distance of travel, and the volume, mass or the density of transported goods.

The step-by-step approach for planning stage of the data collection can be shown as in Figure 8.

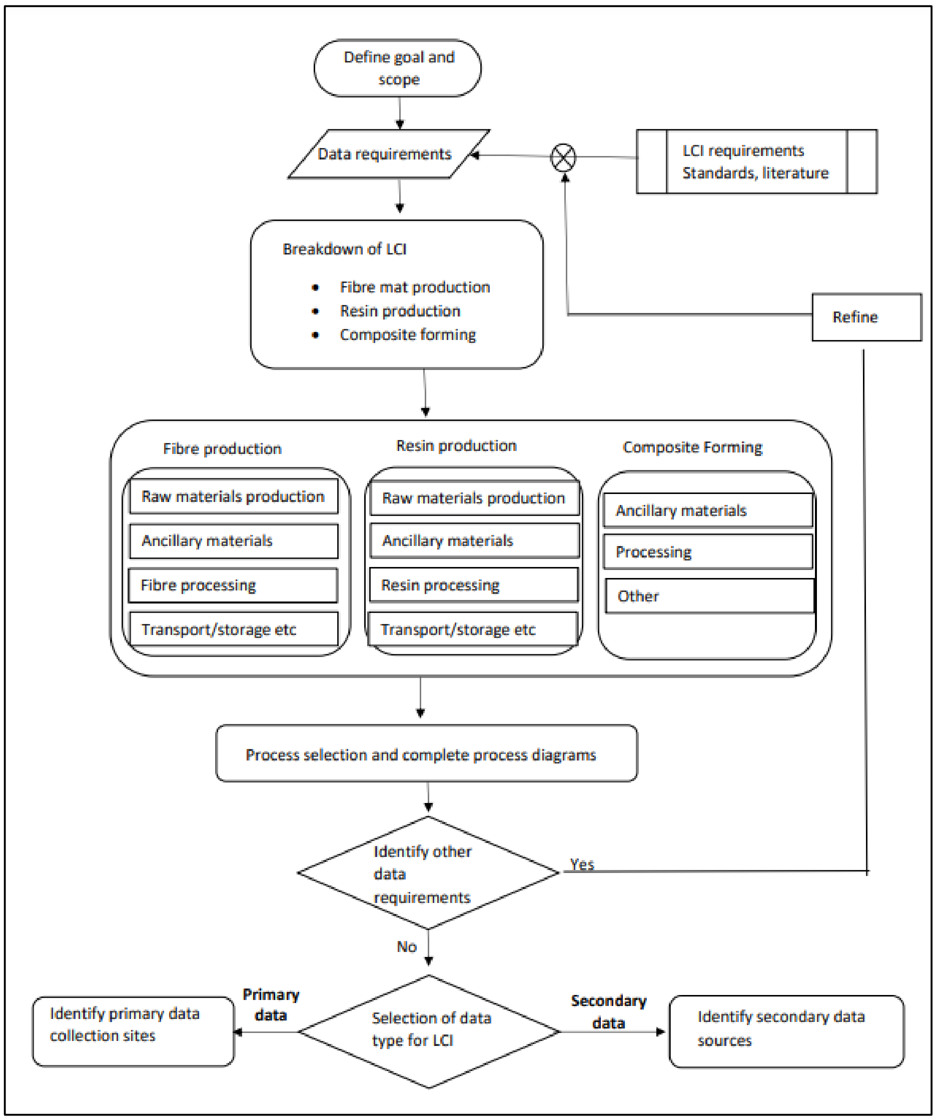


Figure 8 Step-by-step decision diagram for planning the data collection for LCI

DATA COLLECTION PHASE

Once the data requirements are identified at the planning phase, the next step is to customise a LCI template for data collection. Generic templates for data collection can be found in the literature and these can be customised according to the data requirements of the study. Depending on the complexity of the system and the goal and scope of the study these templates should be developed and revised. This could also include several other supporting work sheets to include details such as:

- Instructions, definitions and guidelines on completing and navigating the data collection template
- Data collection in phases e.g., fibre production, resin production and composite forming
- References: the sources of original data to endure transparency and reproducibility
- Equations and calculations used
- Assumptions
- Feedback: all additional comments, questions and clarifications regarding the data provided
- Contact details: metadata on the data providers, details of the LCA practitioner who collects information and reviewers etc

Once the LCI template has been finalised and refined, the next step is to complete the data gathering process by carrying out measurements and recording data on the template. The questions and clarifications arise during the data collection should be addressed and recorded on the template. If any assumptions are made in the process, these should be clearly defined. This is an iterative process as illustrated in Figure 9.

The uncertainty of measurements and variability in the measured data can also recorded in the data collection template. The pedigree matrix approach (composed of data quality indicators such as reliability, completeness, temporal correlation, geographical correlation and technological correlation) can also be used as a self-assessment of data quality by the LCA practitioner. Data validation prior to completing the data set would be a very important step in this proposed method to iron out discrepancies and eliminate errors and will be discussed in detail.

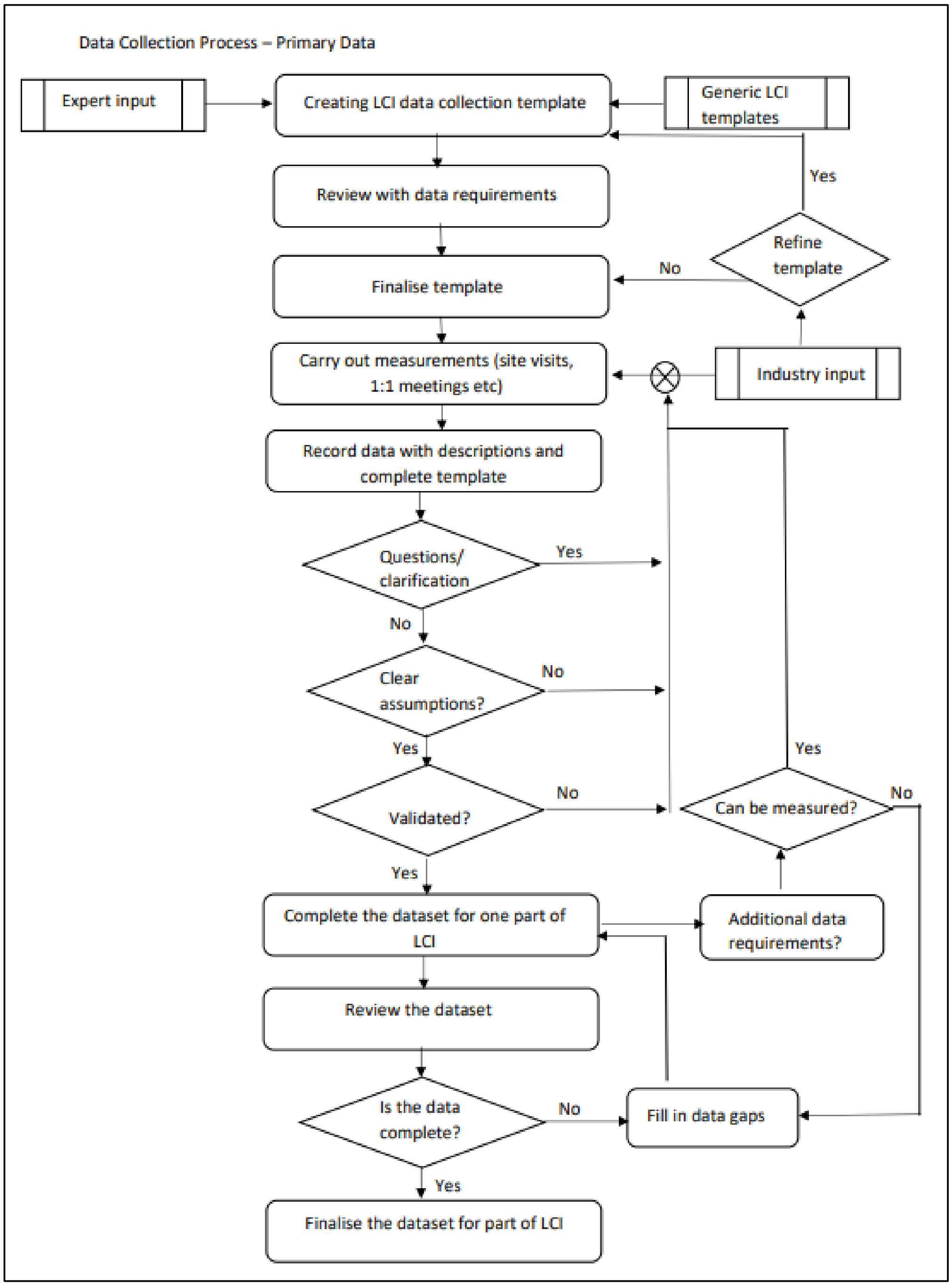


Figure 9 Step-by-step decision diagram for LCI data collection

FROM MEASUREMENTS TO LCI DATA FOR COMPOSITES

The data collection method chosen in a study will depend on the required precision, the type of data to be collected (e.g., a specific period or batches), skills of the person collecting data and the acceptance of the method by the intended audience. International standards should be used for measurements where possible to ensure the repeatability and comparability of measurements. These guidelines aim to aid in interpreting direct measurements (e.g., electricity, natural gas, petroleum) to LCI data (e.g., energy) which are collected from the original source (primary data).

Flow of a typical LCI data calculation is shown in Figure 10.

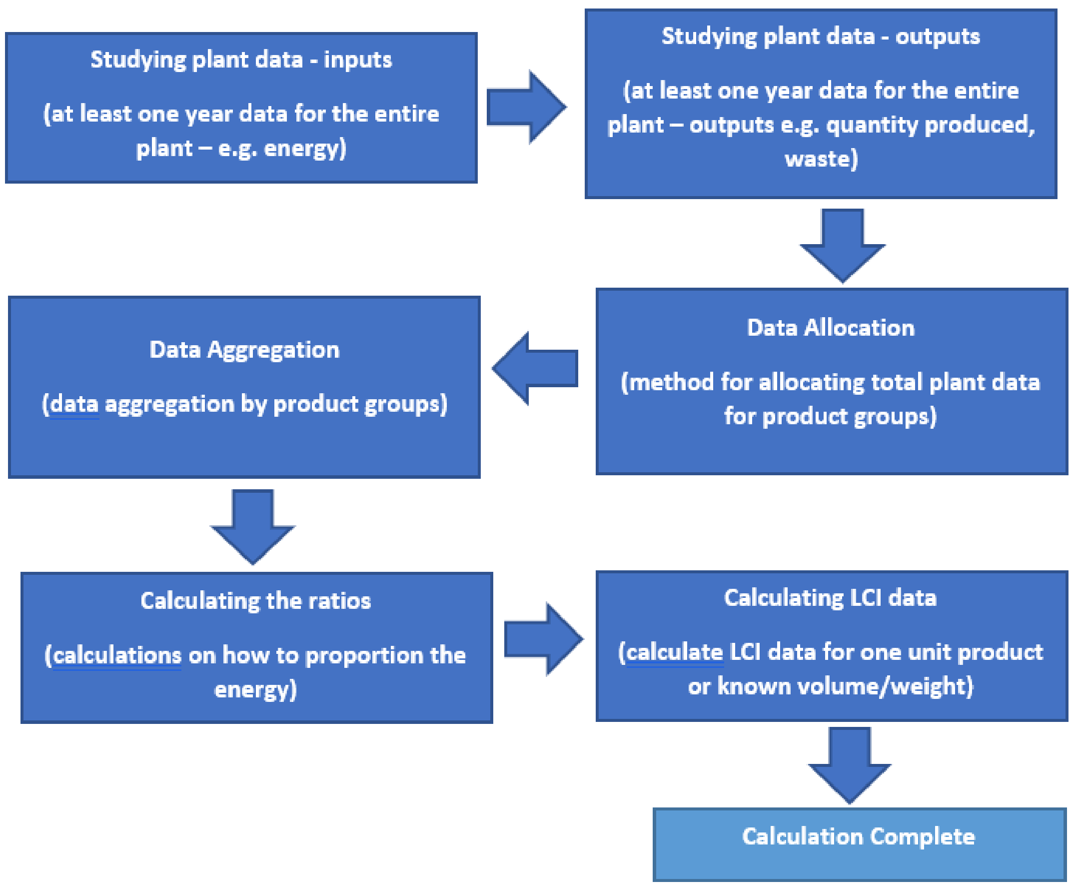


Figure 10 Flow of a typical LCI calculation

STUDYING PLANT DATA – INPUTS

It is useful to obtain the data for inputs e.g., energy, raw materials, water, ancillary materials for the entire plant for a specific period (at least for a year). This could be either done by collecting data from recorded sources (utility bills, inventory or stock records, smart meters etc) or by having a data collection method in place at the plant. The period of closures, maintenance, machinery break down etc should also be recorded and accounted. If there is any historical data that has been recorded based on a different method or model, they can be used for the purpose of comparison to validate the data. For example, fuel consumption data can be found in purchase receipts or utility bills, delivery receipts, contract purchase or firm purchase records, stock inventory documentation and metered fuel documentation etc.

Energy from different sources (electricity, natural gas or fuel) must be carefully differentiated and studied separately. It is advisable to use SI units in measurements and non-SI units (lbs, gal, BTU etc) should be strictly avoided. If non-SI units are used in measurements, they can be easily converted to SI units using universally valid conversion factors.

Table 7 below lists some inputs in a typical composite processing plant as an example. Please note this list does not contain all the inputs.

Table 7. Example - List of inputs in a typical composite processing plant

INPUT	Unit	Quantity
Electricity	kWh	250,000,000
LPG	kg	100,000
LNG	kg	100,000
Petrol	L	20,000
Diesel	L	40,000
Water	m^3	100,000

RAW MATERIALS	Unit	Quantity
Glass fibres	kg	20,000,000
Carbon fibres	kg	10,000,000
Epoxy resin	kg	25,000,000
Polyester resin	kg	10,000,000
Solvents	kg	50,000
Binder resin	kg	100,000
Carrier film	kg	150,000

STUDYING PLANT DATA – OUTPUTS

This will include studying outputs for the entire plant including the quantity of finished products produced within a specific period. Outputs should also include waste (in the forms of raw material waste, industrial discharge and water) depending on the scope of the study.

Table 8 Example – List of outputs in a typical composite processing plant

OUTPUT	Unit	Quantity
GF-Epoxy composites	kg	10,000,000
GF-Poly composites	kg	7,000,000
CF-Epoxy composites	kg	5,000,000
CF-Poly composites	kg	3,000,000
Wastewater	m^3	50,000
Industrial waste discharge	kg	100,000
Raw material waste	kg	6000

DATA ALLOCATION

It is recommended and good practice, that data allocation used as a technique for collecting and measuring data for use in the LCI. According to ISO 14044 [4], data allocation can be conducted using a parameter that is interrelated to the environmental impacts of the product such as product volume, weight, price or unit of a product.

Examples of types of data allocation that can be used in measurements and calculations in LCI for composites are given in Table 9 below.

Table 9 Examples of data allocation methods for composites

Method	**Description**
By volume	Measure and calculate using ratio by volume of the composite panel. E.g.: 1m (L) X 1m (W) X 5mm (T) LCI data is directly proportional to the volume.
By weight	Measure and calculate using ratio by weight of the composite (E.g.: 1 kg of composite). LCI data is proportional to the weight.
By weight/volume of raw materials	Measure and calculate using ratio by weight of the raw material. E.g.: 1 ton of glass fibres or 1m^3 of resin LCI data is proportional to the weight of the selected raw material
Proportioned by energy use	Measure and calculate the LCI data as a proportion of energy E.g.: 1GJ of energy in terms of electricity, fuel and gas to produce X number of composite panels or X area of composites

Please note that data allocations methods are not limited to those listed on the table above.

DATA AGGREGATION AND CALCULATING PROPORTIONS

It is useful to have a clear picture of the entire plant where the data is collected or measured from. The plant may include multiple floors or buildings that are used to process different types of raw materials to produce composites or composite products. Therefore, the plant data should be allocated by the groups of products or to aggregate the individual-product data into product-group data first.

E.g., Aggregating data by volume or weight
It is important to select a parameter that is interrelated to the inputs and outputs of the LCI to aggregate the data. The selected parameter must be used as the standard in every calculation to maintain the efficiency of LCI.

Figure 9 illustrates an example of composite plant (Company A) which has products groups (Fibre X, Y and Z) subgroups (Resin 1 and 2) and final products (1,2,3,4,5 and 6).

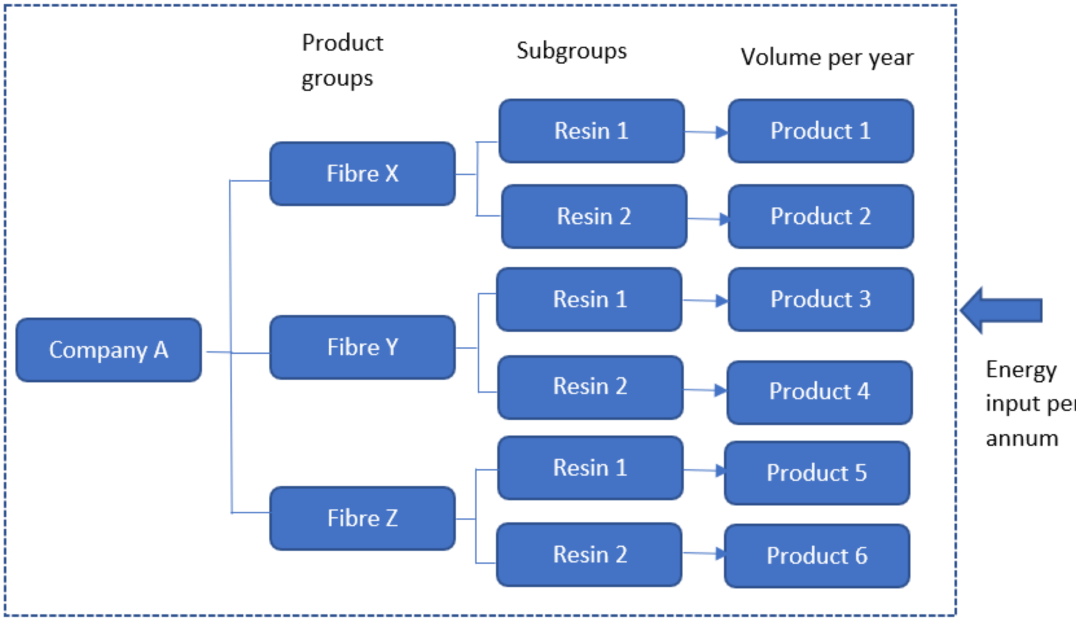


Figure 9 Example of a composite plant that produce different products

Calculations: Electricity and natural gas consumption can be calculated separately using the equations below.

$$E_{P1} = \frac{V_{P1}}{V_T} \times E_T \qquad (Equation\ 1)$$

E_{P1} – Electricity consumed to produce Product 1 in a year
V_{P1} – Volume of Product 1 produced in a year
V_T - Total volume of products produced in a year
E_T – Total electricity consumption of the plant in a year

Then, the value of E_{P1} can be proportioned to calculate electricity required to produce a specific volume (z) of Product 1 (E_{P1Z})

$$E_{P1z} = \frac{E_{P1}}{V_{P1}} \times z \qquad (Equation\ 2)$$

E_{P1Z} – Electricity used to produce volume (z) of Product 1
E_{P1} – Electricity consumed to produce Product 1 in a year
V_{P1} - Volume of Product 1 produced in a year

Assumptions: The electricity or natural gas consumed to manufacture different products are the same and proportional to the volume.

If the electricity consumption differs between the products and processes, the consumption must be captured by accounting the machine power at each production step.

$$E_i = \frac{P_i \times T}{V_{out}} \qquad (Equation\ 3)$$

E_i - Electricity consumed at production step (i)

P_i - Machine power of production step (i)
T - Machine run time
V_{out} - Volume or quantity produced at step (i)

CALCULATING LCI DATA

The data categories in LCI mostly are raw materials, energy (used in raw materials production, transport, processing etc) and emissions (to air, water and soil as a result.

The data for raw materials is not suitable for allocation out of the entire plant data as these are specific to each product group. The data associated with raw materials should be acquired independently of all other items. The raw materials consumption for one unit of product/specific weight/volume can be proportioned:

- by obtaining the standard consumption rate from cost/costing accounting records
- by allocating the raw materials consumed by a product group
- by using the amount of the constituent product as the amounts of raw materials consumed if the consumption cannot be obtained from the above two methods

Once the consumption for unit product/specific volume or weight is calculated, embodied energy (primary energy that is associated with the extraction, processing and transportation of that material from cradle to factory gate) must be calculated to use in LCI depending on the goal and scope of the study.

Energy can be measured as electricity, natural gas or fuel consumption which should be proportioned to the functional unit chosen for the study (one product unit or specific weight/volume by proportioning the data for the product group). Identification of energy sources and flows – energy consumption by different sources (electricity, natural gas, and fuel) must be recorded individually, and values can be added together to reach a final value for energy consumption of the plant for a specific period of time. It is highly recommended to record the conversions and additional information that may have influenced the energy consumption within individual processes. These factors may include – details of vehicles (make, age, load, distance travelled), machinery (make, age, power, maintenance record, idle time etc). For example, the electricity used to produce unit of glass fibre - epoxy composite can be calculated at the processing level by accounting each machinery used or by proportioning the total electricity consumption of the plant by the number of units produced.

The accuracy of the calculations of electricity/natural gas or fuel will depend on using the correct conversions when recording in LCI.

For example:

1. Electricity consumption to produce 1 tonne of glass fibre can be assumed as 500 kWh which can be extracted from company records. This value needs to be converted into MJ or GJ to be included in the LCI using the conversion (1kWh = 3.6 MJ). The reported value on the LCI for energy used as electricity to produce 1 tonne of glass fibre should be 1.8 GJ

2. Natural gas consumption to process $1m^3$ of carbon fibre-epoxy composite panel can be assumed as $12m^{3,}$ the conversion used to convert the values to energy should be recorded ($1GJ = 25.5m^3$). The value to record on LCI for energy used in terms of natural gas should be 0.47 GJ

There are two types of emissions that can be recorded in the LCI: direct emissions (emissions occur from sources that are owned or controlled by the company, for example emissions from combustion in owned or controlled boilers, furnaces, vehicles etc and emissions from chemical production or processing equipment) and indirect emissions (emissions occur from the generation of purchased electricity and heat consumed by the company). Purchased electricity is defined as the electricity that is purchased or otherwise brought into the boundary of the company and these emissions physically occur at the facility where the electricity is generated [33].

The emissions from combustion sources (vehicles and machinery) can be estimated either by direct measurement or analysing of fuel input [34]. Direct measurement of emissions can be done using Continuous Emissions Monitoring System (CEMS) method which measures the pollutants emitted into the atmosphere from combustion or industrial processes. The fuel analysis method calculates emissions by determining a carbon content of fuel combusted using fuel-specific information or default emission factors.

Following are some examples of equations that can be used in fuel analysis method [34],

Example 1

When fuel consumption is known in mass or volume units with no other information, the following equation can be used.

$$\text{Emissions} = \text{Fuel x } EF_1 \qquad (Equation\ 4)$$

Where, Emissions = mass of CO_2, CH_4 or N_2O
Fuel = mass or volume of fuel combusted
EF_1 = CO_2, CH_4 or N_2O emission factor per mass or volume unit

Example 2

When the actual fuel heat content and fuel use is known in energy units (e.g., natural gas), the following equation can be used to calculate emissions.

$$\text{Emissions} = \text{Fuel x HHV x } EF_2 \qquad (Equation\ 5)$$

Where, Emissions = Mass of CO_2, CH_4 or N_2O
Fuel = Mass or volume of fuel combusted
HHV = Fuel heat content (higher heating value) in unit of energy per mass or volume of fuel
EF_2 = CO_2, CH_4 or N_2O emission factor per energy unit

Example 3

The following equation can be used to calculate CO2 emissions when actual carbon content of the fuel is known.

$$\text{Emissions} = \text{Fuel x CC x 44/12} \qquad (Equation\ 6)$$

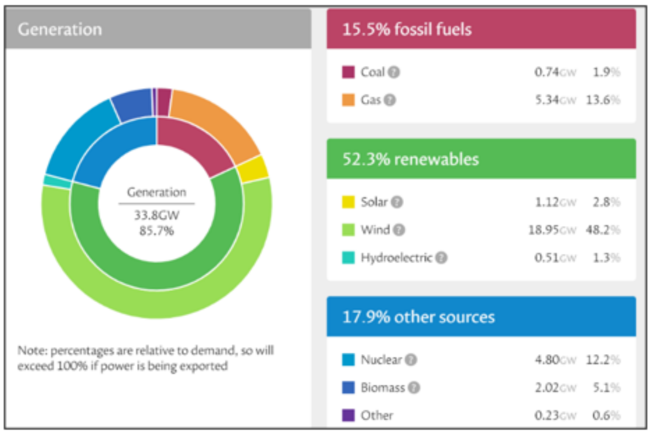
Where, Emissions = Mass of CO_2 emitted
Fuel = Mass or volume of fuel combusted
CC = Fuel carbon content, in units of mass of carbon per mass or volume of fuel
44/12 = ratio of molecular weight of CO_2 to carbon

By using appropriate equations with the fuel consumption and other inputs, the emissions of CO_2, CH_4 or N_2O can be calculated. These values for emissions can be recorded in LCI with relevant information and can be converted into respective environmental classification factors (Global warming potential, acidification potential etc) in LCIA.

To calculate, indirect emissions arising from electricity production would require the details of up-to-date information of the national grid in the demographical area. The emissions should be calculated according to the energy conversion technologies used such as nuclear, fossil fuel, solar, wind, hydro power etc.

Example for calculating CO_2 emissions in electricity production is shown below.

Electricity generation – breakdown in UK



Source: National Grid – Live (https://grid.iamkate.com/)

CO_2 emissions intensity

Generation Source	kg CO2 per kWh
Open Cycle Gas Turbine	0.5
Closed Cycle Gas Turbine	0.5
Oil	0.65
Coal	0.9
Nuclear	0.005
Pumped Storage	0.02
Non Pumped Storage Hydro	0.005
Wind Onshore	0.00464
Wind Offshore	0.00525
Solar	0.058

Source: data is from The Parliamentary Office of Technology document – Carbon Footprint of electricity generation

Figure 10. The information required to calculate the emissions in electricity production [35][36]

CO_2 emissions by coal, gas, solar, wind or hydro power can be calculated by multiplying the % contribution to the national and CO2 intensity factor.

CO2 emissions in electricity production by coal = The amount of electricity consumed (kWh) x percentage of contribution to national grid by coal (1.9) x CO2 intensity factor of coal (0.9 kg per kWh)

Total CO2 emissions in electricity production can be calculated by adding each energy conversion technology that is used in the national grid.

RECOMMENDATIONS AND FUTURE WORK

The data quality issues were reviewed in this study to provide guidance and recommendations for LCA practitioners in data collection for LCI with reference to composite manufacturing. Conducting data flow pathways for chosen data points deemed to have highlighted issues such as using aged data with new references, lack of transparency, reproducibility and inconsistency within the data sets etc. It was observed that LCA results obtained through estimations and assumptions may include biased (not reflect the true overview) and wrong conclusions. This can be addressed and limited by adopting more transparency in data collection and recording and by having a good quality control process in place. A comprehensive and quantitative LCA study would be preferable to avoid any misinterpretations but may not be possible in practice. Incomplete LCA study (may include poor system boundaries, estimates, assumptions, data, quality control etc) would not reflect an honest overview of the scenario and will not serve the purpose. Goal and scope and system boundaries of a study should not be defined to suit the LCA results to claim the environmental superiority of a product or process over another.

It was also understood that there is no clear guidance or methodology in place for data collection and data interpretation in LCI and not all LCA studies provide a complete description of their data collection process and a transparent account of their LCI data. The aim of this study has been to provide some recommendations and guidelines for LCA practitioners to follow in data collection for composite production. The proposed framework will provide some guidance to improve the LCI data quality to produce more robust and reliable LCA results.

VALIDATION TECHNIQUES

Data validation within the LCI would eliminate progression of error and inaccuracies of data to the next phase of LCA. Individual data values should be validated after collection and prior to aggregation and calculation to maintain quality of data in LCI. It is important the validation is done by professionals with data collection experience following a self-assessment by the person who is collecting or measuring the data.

Validation may include:

- relevance of the data collected (in line to the scope of the study)
- data correlation to the flow diagrams produced
- use of clear measurement techniques/methods
- definitions of assumptions
- recalculation of calculated data
- use of standard unit conversions where non-SI units is used
- identification of any data gaps by mass balance calculations (to check the input and output values are balanced)
- consistency of data allocation method
- cross-checking with data obtained from different sources e.g., comparing measured data with expected values from estimates or theoretical calculations and vice versa
- benchmarking data collected for specific process versus data relative to the same industrial sector or technology

ISO standards [4] [5] state the validation as a requirement for all data included in the study and mainly the checks for completeness and consistency are done at the LCI. Validation is a general concept covering many different aspects, such as data relevance, correlation, units and mass balances and review by another person than one responsible for collection of data.

The critical review of the LCA study which is done upon the completion of study should check that adequate validation has been done in LCI. Although, it is not the purpose of the critical review to re-do the validation, it may be necessary for the reviewer to perform factual validation of the data used which are most impactful for the conclusion.

RECOMMENDATIONS FOR DATA RECORDING

ISO standards [4] [5] require the results, data, methods, assumptions and limitations to be clearly, fairly and accurately reported, and in sufficient detail to allow the intended audience to comprehend the results of the study. However, it was found the data recording is not consistent and lack of clarity prevents the data being used for other studies and reproducible.

The recommendations in documenting an individual data value may include:

- amount
- the unit of measurement
- the details to distinguish the data value from other data in the series

The individual data or the data series should have necessary identifiers (metadata) to place the data in its appropriate context (data collection/measurement techniques and/or applications). For example, any references must be recorded either directly or indirectly to the data collection methods/measurement techniques, geographical location, time and other conditions pertaining to the validity of the collected data. It is important, the aspects that affect data variability such as geographical, technological information is considered and documented clearly to avoid any misinterpretation. The documentation may also include any specific assumptions, limitations and/or bias that affects the representativeness and/or applicability of data. Unnecessary calculations (e.g., unit conversions or proportioning) may introduce errors and obscure the original data and they should be avoided at this stage of data recording.

5.3 FUTURE WORK

Assessing all aspects of LCI data quality and gaps in data collection in LCA for composites is a challenging task. This was attempted by conducting a scoping study in 2021/2 to identify some of the data quality and measurements gaps that exist within the LCA framework for composites and thereby recommending a step-by-step approach for data collection, guidelines for converting measurements to LCI data, recommendations for data validation techniques and data recording that can be adopted in LCI to improve the data quality. However, it is important to trial the proposed guidelines and recommendations in real life situation by carrying out a feasibility study for composites. A case study would help to understand the potential weak and strong points in the guidelines to improve. Further developments in standards for data collection and reporting are needed to adequately clarify and address data quality, variability an uncertainty as the use of LCA as a decision support tool continues to grow in achieving net zero targets by industry. It is also important to understand the effects of data quality and variability in each data point may have on the outcome of the LCA results and to qualitatively address these impacts by a sensitivity analysis.

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