

Deliverable number: 6.1



DACOMAT - Damage Controlled Composite Materials

LCA database of environmental impacts to inform material selection process

Callum Hill, Andrew Norton

JCH Industrial Ecology Ltd

Deliverable details

Document name: LCA database of environmental impacts to inform material selection process

Responsible partner: JCH Industrial Ecology Ltd

Work package: 6

Task: 6.1

Due date: 30/06/2018

Delivery date: 27/06/2018

Dissemination level	
X	PU = Public
	CO = Confidential, only for members of the consortium (including the EC)
	Classified, information as referred to in Commission Decision 2001/844/EC.
Deliverable type	
X	R: Document, report (excluding the periodic and final reports)
	DEM: Demonstrator, pilot, prototype, plan designs
	DEC: Websites, patents filing, press & media actions, videos, etc.
	OTHER: Software, technical diagram, etc.

Disclaimer:

The information in this document reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Introduction

The purpose of this report is to provide advice on relevant LCA data for use by project partners. The deliverable is a database which gives environmental impact data on Global Warming Potential and Embodied Energy for materials and processes relevant to the project. The description of D6.1 from the proposal is as follows:

‘An inventory will be created of the component materials which will form the basis of the composites. This will be informed by the use of background data from the ELCD and Ecoinvent databases. Where partners have already conducted their own LCAs, the information will also be incorporated into the database, where this is compatible. Where there are data gaps, these will be filled by conducting searches of the scientific literature and any published environmental product declarations. Where this is not possible, modelling will be used. All of this information will be incorporated into an excel spreadsheet. A report will accompany this spreadsheet.’

Background to Life Cycle Assessment

Life cycle assessment (LCA) is a tool that has been developed in order to analyse and quantify the environmental burdens associated with the production, use and disposal of a material or product and is arguably the best way of quantifying this information (Hill, 2011). The foundation underpinning any LCA is data about a process. In order to conduct an LCA it is first necessary to determine the goal and scope (i.e. what is the purpose behind conducting the LCA and what is being included in the study). The scope must define what the system boundaries are in the study and the functional unit must be declared. For many purposes, the system boundary can be defined as ‘cradle to gate’, that is the manufacture of a specific product in a factory to the point at which it leaves the facility (modules A1-A3 in EN 15804). This gives the most accurate LCA, because this stage of a product life cycle involves the fewest assumptions and the data gathering process is relatively straightforward. Life cycle assessment is not static and there are ongoing programmes dealing with improving various aspects of this methodology (Finnveden et al. 2009). It is important that the correct decisions are made regarding the choice of materials for the built environment and LCA can be used as a means for informing those choices. This requires that LCA is used correctly and that the decision support tools allow for comparability between products (Forsberg and Malmborg 2004, Happio and Viitaniemi 2008a, Ding 2008, Audenaert et al. 2012, Shrestha et al. 2014).

Goal and scope definition

The goal and scope stage comprises the writing of a series of statements at the beginning of the process which tell the reader the reason why the LCA was performed, who is doing the study, who the client is and what is covered in the LCA. It is at this stage that the system boundary is defined. For example, the purpose may be to undertake an LCA of the manufacturing process only (cradle to factory gate), or the whole service life may be included. Additional parts of the lifecycle, such as recycling and disposal may also be included. The purpose of the LCA may be simply to report the environmental burdens associated with a product or process (referred to as an attributional LCA), or it may examine the consequences of changing various parameters or assuming different scenarios (called consequential LCA). It is also necessary to specify what is the subject of the LCA. This is referred to as the declared unit if cradle to factory gate is being analysed, or the functional unit, if other parts of the lifecycle are also being studied. Another important consideration when studying the environmental impacts associated with a product or process is the timescale involved and it is

important that this is also defined at this stage. It is also a requirement to specify what allocation procedures were used during the analysis.

Life cycle inventory

This phase of the analysis requires the assembly of all of the information about the process. In order to do this an imaginary system boundary is drawn around the process and all of the material and energy inputs and outputs are quantified. This process is usually divided into the different life cycle stages, manufacture, service life, end of life, disposal. Once the life cycle inventory (LCI) phase of the analysis is complete then data gaps are identified. In some cases it is possible to collect the missing data, but where this is not possible, 'reasonable' assumptions have to be made. During this phase, mass balance calculations are also performed. This is a very useful tool for identifying data gaps and is based upon the principle that the mass of all matter going into the system under study should equal that of all the matter exiting the system. At some stage, the data gathering process has to be terminated and the point at which this occurs is determined by cut-off criteria. Data falls into two principal categories: primary (foreground) and secondary (background) data. Primary data is that which has been gathered by the LCA practitioner and may include utility bills, delivery notes and other information that is directly linked to the process. Secondary data is that which has not been directly obtained, but is more generic in nature; for example if wooden pallets are used to ship the product, then it is highly unlikely that a full inventory of the pallet would be made.

Ultimately, what should result from such an analysis is a table (called an input-output table) that represents flows of materials and energy to and from nature (the ecosphere). All of the foregoing is complicated enough, but if the factory in question also produces other products (co-products) then the question of allocation of the environmental burdens to the different components in the inventory to the declared unit must be considered. For example, a utility bill for a factory will give the total electricity consumption for a year, but if the factory makes ten products then a means of correctly allocating the electrical energy (and associated environmental burdens) to the analysed product must be derived. The collection and analysis of data invariably leads to issues regarding commercial confidentiality, which can cause problems, especially when the LCA has to meet adequate levels of transparency in order to be credible.

Life cycle impact assessment

Once the LCI phase has been completed, it is then necessary to quantify the environmental burdens, during the life cycle impact assessment (LCIA) phase. At this stage there are several further complications that have to be considered. The biggest problem is deciding how to report the environmental impacts. There is still discussion as to how to do this in order to properly report the environmental burdens, but a consensus has been developing over the past decade or so. The principle is to aggregate the environmental implications associated with the flows to and from nature into a small (but nonetheless meaningful) set of indicators. This methodology has essentially distilled down into two main approaches, referred to as midpoint and endpoint indicators (Bare et al. 2000, Jolliet et al. 2004, Hauschild et al. 2013). In the midpoint approach, the environmental burdens are grouped into similar environmental impact categories (e.g., global warming potential, ozone layer depletion, freshwater eutrophication, etc.). The endpoint approach seeks to model the chain of cause and effect to the point of the evaluation of damage, which makes for simpler reporting with fewer indicators, but has a higher level of uncertainty. Impact categories are reported in terms of impact on human health (e.g., DALY, disability adjusted life years), or on ecosystems (e.g., species

loss). Some systems have even gone so far as to aggregate all of the impacts into one category (e.g., ecopoints), but the values reported using this approach have such high uncertainties associated with them as to be effectively meaningless. The environmental impacts are calculated using a variety of models (over 150) which attempt to determine the impacts of processes upon the environment. Examples of such models include:

- Midpoint: TRACI, CML, EDIP, Ecopoints
- Endpoint: Eco-indicator, LIME2
- combined midpoint and endpoint: ReCiPe (Bare et al. 2000), IMPACT2002+ (Jolliet et al. 2003).

The impact categories selected should provide useful information about the product or process taking the goal and scope of the study into consideration. When selecting the impact categories, it is also necessary to select the characterisation factors, which are the units used to report the environmental burden. To consider the example of the climate change impact category, the characterisation factor for this is global warming potential with a 100 year timeframe (GWP100) and the characterisation factor for this is kg CO₂ equivalents (CO₂e).

Another important factor is the correct allocation of environmental burdens to different co-products if the system under analysis produces more than one product. Examples of this include the allocations between cereal and straw, or meat and wool in agricultural production systems (Brankatschk and Finkbeiner 2014). Ideally, allocation should be avoided when possible, but in many cases this cannot be done and a choice has to be made regarding the allocation procedure used. Various approaches can be used for allocating environmental burdens, including mass, energy, or economic allocation. Guidance regarding allocation is given in ISO 14040 and ISO 14044, recommending a hierarchy of choice for allocation methods.

Environmental product declarations

All of the above illustrates that there is considerable potential for uncertainties to creep into LCA, even when they are performed with the best of intentions. Nevertheless, considerable progress has been made in this field in the past decade. Perhaps one of the most significant developments has been the introduction of environmental product declarations (EPD). In order to develop a framework that allows for comparability of environmental performance between products, ISO 14025 was introduced. This describes the procedures required in order to produce Type III environmental declarations. This is based on the principle of developing product category rules (PCR) which specify how the information from an LCA is to be used to produce the EPD. A PCR will typically specify what the functional unit is to be for the product. Within the framework of ISO 14025, only the production phase (cradle to gate) of the lifecycle has to be included in the EPD, forming what is known as an information module. It is also possible to include other lifecycle stages, such as the in-service stage and the end of life stage, but this is not compulsory. ISO 14025 also gives guidance on the process of managing an EPD programme. This requires programme operators to set up a scheme for the publication of a PCR under the guidance of general programme instructions. There have been other standards issued that apply to the construction sector in order to ensure greater comparability of the environmental performance of products. ISO 21930 gave some guidance on both PCR and EPD development, but this was recently replaced in Europe by EN 15804, which is a core PCR for building products and it is therefore considerably more detailed and prescriptive than ISO 14025. ISO 21930 is currently being revised.

The primary purpose of an EPD according to ISO 14025 is for business to business (b2b) communication, but an EPD can also be used for business to consumer (b2c) communication. In the latter case, there are further requirements upon the process, which apply especially to the verification procedures. In any case, ISO 14025 encourages those involved in the production of an EPD to take account of the level of awareness of the target audience. Standards are increasingly removing the flexibility (and uncertainty) that was once associated with determining the environmental performance of products and services. This should make it much easier to compare the environmental impacts of products within a product category in the future.

There have been other standards issued that apply to the construction sector in order to ensure greater comparability of the environmental performance of products. ISO 21930 gave some guidance on both PCR and EPD development, but this was recently replaced in Europe by EN 15804, which is a core PCR for building products and it is therefore considerably more detailed and prescriptive than ISO 14025 (ISO 21930 is currently being revised). The different life cycle stages are divided into modules in EN15804, modules A1-A3 cover the production stage, A4-A5 the construction process, B1-B7 the use stage and C1-C4 the end of life stage; beyond this is the 'after-life' stage (D). These are listed in Table 1. The publication of this standard ensures harmonisation of core PCRs for building products in Europe. It is mandatory to report stages A1-A3, with the other stages being included for any reporting beyond cradle to factory gate.

Table 1: Different life cycle stages defined in EN 15804

Module	Life cycle stage	Description
A1	Production	Raw material supply
A2	Production	Transport
A3	Production	Manufacturing
<hr/>		
A4	Construction	Transport
A5	Construction	Construction/installation
<hr/>		
B1	Use	Use
B2	Use	Maintenance
B3	Use	Repair
B4	Use	Replacement
B5	Use	Refurbishment
B6	Use	Operational energy use
B7	Use	Operational water use
<hr/>		
C1	End of life	De-construction/demolition
C2	End of life	Transport
C3	End of life	Waste processing
C4	End of life	Disposal
<hr/>		
D	Beyond building life cycle	Reuse/recovery/recycling

What is required is an agreed standard way of reporting the environmental burdens associated with a specific functional unit, which has led to the development of product category rules (PCR). These PCRs have been developed by different organisations which have set up EPD programmes (examples in Europe include the International EPD® system based in Sweden and the Institut Bauen und Umwelt in Germany). Since the introduction of ISO 14025, there has been a proliferation of EPD systems, with their own PCRs. ISO 14025 encourages the operators of EPD programmes to harmonise their

methods and PCRs and in Europe this has resulted in the creation of 'ECO' a platform for rationalising EPDs, involving 11 EPD operators within Europe. This involves mutual recognition of EPDs, and the creation of common PCRs, working from agreed core PCRs (such as EN 15804 in the built environment).

Table 2: Different environmental impact categories according to EN 15804

Impact category	Parameter	Unit
Global warming	Global warming potential (GWP)	kg CO ₂ equiv
Stratospheric ozone depletion	Ozone depletion potential (ODP)	kg CFC 11 equiv
Acidification of soil and water	Acidification potential (AP)	kg SO ₂ equiv
Eutrophication	Eutrophication potential (EP)	kg (PO ₄) ³⁻ equiv
Photochemical ozone creation	Formation potential of tropospheric ozone (POCP)	kg ethane equiv
Depletion of abiotic resources-elements	Non-fossil resources abiotic depletion potential (ADP-elements)	kg antimony equiv
Depletion of abiotic resources-fossil fuels	Fossil resources abiotic depletion potential (ADP-fossil fuels)	MJ

In theory, the introduction of EPDs which use common PCRs means that it should be possible to compare different building materials in terms of environmental impact. However, while it may be possible to make choices based upon the environmental impacts associated with the manufacture of products, the use phase and end of life phase also need to be considered in order to get the whole picture. Important considerations when examining the environmental consequences of the use of different materials must include the service life of the product, maintenance requirements and performance in service, especially with respect to the impact on the operating energy of the building. This can involve assumptions being made regarding life span, maintenance, end of life scenarios, etc., which will have a critical impact upon the outcome of the LCA.

Embodied Energy

The embodied energy of a material or product used in a structure or product is often defined as the **primary** energy used in the manufacture, which includes all of the energy used in the production, as well as the primary energy used in the transport of materials and goods required for the production process. This definition relates to the initial embodied energy, which is related to the cradle to factory gate stage (modules A1-A3, EN 15804) of the product life cycle. In some definitions, the transport to construction site (A4) and the energy used on site for the erection or installation of the product (A5) is also included. The units used are generally MJ per unit mass, or volume, or per defined functional unit, although some workers report this as kWh (=3.6 MJ). Transport of materials to site can have a major impact on the embodied energy of the construction materials.

The embodied energy is invariably reported according to the cumulative energy demand (CED) method, which states that the embodied energy is assessed as the primary energy used for the manufacture, use and disposal of an economic good (product or service), or which may be attributed to it with justification. The method distinguishes between non-renewable and renewable energy use. The cumulative energy demand (CED) represents the primary energy used (both direct and indirect) during the life cycle of a product (Huijbregts et al. 2006). This includes the energy consumed during the extraction, manufacturing and the disposal of the product and raw and auxiliary materials. Different methods for determining the primary energy demand exist. For example, the lower or higher heating values of primary energy sources may be used, the use of renewable energy resources may not be included or it may be reported separately. Fay and Treloar (1998) define primary energy as 'the energy required from nature (e.g., coal) embodied in the energy consumed by the purchaser

(for example, electricity) and the energy used by the consumer as ‘delivered energy’. This means that a process using 1 MJ of electricity in one region of the world may have a different embodied energy compared to an identical process using 1 MJ of electrical energy in another part, because the grid mix in the two regions is different.

Dixit et al. (2012) noted that some research workers do not include renewable energy in their definition of embodied energy and also found that the use of different information sources and the failure to distinguish between primary or secondary energy could lead to errors as high as 40% when reporting embodied energy. They stated that there is a need to develop a common methodology to accurately determine the embodied energy associated with buildings and that there is a need to develop a complete and robust database of embodied energy information. There is the widely-used University of Bath Inventory of Carbon and Energy database (e.g., Lee et al. 2011). However, this (and others) may not necessarily be reliable sources of information. For example, the Bath ICE database has been shown to inaccurately report data for harvested wood products (Hill and Dibdiakova 2016). Cabeza et al. (2013) and Jiao et al. (2012) note that there is a relationship between embodied energy and GWP for primary production, for some building components and that there is a link between embodied energy and cost of buildings, which is related to the energy intensity per unit GDP for that country.

It is necessary to define the meaning of primary energy, since it is not always clear that the primary energy has been used when the embodied energy is reported. The primary energy is defined as the energy measured at the natural resource level, i.e. the energy found in nature that has not been subjected to any conversion process through human intervention. This is the energy used to produce the end-use energy which includes the energy used in the extraction, transformation and distribution to the user (Fay et al. 2000). Measurements of embodied energy are only consistent if they are based upon primary energy but if delivered energy is used, the results are misleading. Unfortunately, there is a lack of clarity and incomparability in the reporting of embodied energy (Dixit et al. 2010, 2012).

The difference in energy intensity reported for onsite energy use and for primary energy for different composite manufacturing processes is illustrated in Table 3.

Table 3: Energy Intensity of Forming (MJ/kg)

Process	Primary energy	Onsite energy
Autoclave molding	66.8	22.3
Hand lay-up	57.7	19.2
Spray up	44.8	14.9
RTM	38.4	12.8
VARI	30.6	10.2
Cold press	35.4	11.8
Preform matching die		10.1
SMC		3.5
Filament winding	8.1	2.7
Pultrusion	9.3	3.1
Compression molding	34.3	11.4
Injection molding	33.7	11.2
Prepreg	120.1	40.0
Sheet molding	10.5	3.5

(Sources: US DoE 2016, Suzuki and Takahashi 2005, Schepp 2006, Song et al. 2009)

The current standards do not provide complete guidance and do not address important issues regarding embodied energy reporting. For example, EN 15804 does not mention embodied energy, although it does require the reporting of energy inputs as primary energy and requires the reporting of the following categories describing resource use:

- Use of renewable primary energy excluding renewable primary energy resources used as raw materials
- Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials

It is important to distinguish between embodied energy, which is associated with the production of a good or service and the inherent (or embedded) energy, which is a physical property of the material. The terms embodied and embedded are sometimes confused in the literature. As noted previously, the embodied energy of a material is the primary energy that is associated with the extraction, processing and transportation of that material from the cradle to the factory gate. In contrast, the embedded energy of a material is a property of that material and can be directly measured. For example, the inherent energy in a wood product can be recovered at the end of its life cycle by incineration, whereas the inherent energy of concrete is zero. The inherent (embedded) energy is reported in EN 15804 in the following categories:

- Use of renewable primary energy resources used as raw materials
- Use of non-renewable primary energy resources used as raw materials

However, different LCA practitioners report data for these categories in different ways. Because in addition, the inherent energy is reported as primary energy in these categories, which does not necessarily represent the true value of the recoverable energy, which is usually more accurately reported for wood as the lower heating value (LHV).

LCA Data

A survey of relevant published LCA data for composites was undertaken. This included the scientific literature, published environmental product declarations, the EcoInvent database and an examination of the European Composites Industry Association EcoCalculator tool.

The following EcoInvent entries exist and are incorporated in the EcoCalculator (January 2018):

Fibres:

- [Continuous filament glass fibre (assembled rovings), at plant RER]
- [Continuous filament glass fibre (wet chopped strands), at plant RER]
- [Continuous filament glass fibre (dry chopped strands), at plant RER]
- [Continuous filament glass fibre (direct rovings), at plant RER]

Thermoplastic resins:

- [Nylon 6-6 {GLO}| market for | Alloc Rec]
- [Nylon 6 {GLO}| market for | Alloc Rec]
- [Polypropylene, granulate {GLO}| market for | Alloc Rec]
- [Polyethylene terephthalate, granulate, bottle grade {GLO}| market for | Alloc Rec]

Polyurethane resin:

- [Methylene diphenyl diisocyanate {GLO}| market for | Alloc Rec]
- [Diethylene glycol {GLO}| market for | Alloc Rec]

Epoxy curing agent:

- [Phthalic anhydride {GLO}| market for | Alloc Rec]
- [Ethylenediamine {GLO}| market for | Alloc Rec]

Epoxy resin:

- [Epoxy resin, liquid {RER}| production | Alloc Rec]

Isocyanate resin:

- [Methylene diphenyl diisocyanate {GLO}| market for | Alloc Rec]

Phenolic resin:

- [Phenolic resin {GLO}| market for | Alloc Rec]

Unsaturated polyester resin:

- [Dicyclopentadiene based unsaturated polyester resin {GLO}| market for | Alloc Rec]
- [Isophthalic acid based unsaturated polyester resin {GLO}| market for | Alloc Rec]
- [Orthophthalic acid based unsaturated polyester resin {GLO}| market for | Alloc Rec]
- [Maleic unsaturated polyester resin {GLO}| market for | Alloc Rec]

Vinyl ester resin:

- [Bisphenol-A epoxy-based vinyl ester resin {GLO}| market for | Alloc Rec]

LCA of Composites

Composite manufacture

A review of the currently available data has been given previously. There is additionally data for pre-preg production given by Suzuki and Takahashi (2005) (Table 4). This gives the impact associated with the production process and does not include the materials. The EuCIA EcoCalculator tool can also be used to calculate impacts for composite production using the following processes: Pultrusion, Resin infusion (RI), Resin transfer moulding (RTM), SMC compounding, SMC compression moulding, Thermoplastic compounding, Long Fibre Thermoplastics compounding, Thermoplastic injection moulding. However, at the time of writing, the ecocalculator tool does not include these processes: Centrifugal casting, Filament winding, Spray-up, Pre-forming, Pre-preg autoclaving, BMC compounding BMC injection moulding.

Table 4: Energy Intensity of Prepreg Production (Suzuki and Takahashi 2005)

Process	EE (MJ/kg)	GWP (kg CO _{2e} /kg)
Resin blending	0.1	
Resin coating	1.4	
Resin impregnation	2.1	
Prepreg winding	0.2	
Atmosphere control	20.8	
Raw material storage	11.5	
Prepreg storage	3.4	
Release paper production	0.5	

The EuCIA EcoCalculator tool was interrogated in order to determine the impacts that are assigned to different processing technologies. This was evaluated by setting the imaginary composite composition to 0.5 kg of glass fibre rovings and 0.5 kg of unspecified polyester resin and including different processes, with the results shown in Table 5. The columns labelled 'difference' give the impacts associated with the process only.

Table 5: Environmental impacts associated with processing

Process	EE (MJ/kg)	Difference (MJ/kg)	GWP (kg CO _{2e} /kg)	Difference (kg CO _{2e} /kg)
Resin infusion	78.12	18.41	4.23	1.25
RTM	66.10	6.39	3.31	0.33
Pultrusion	68.66	8.95	3.55	0.57
No process	59.71	0.00	2.98	0.00

The values obtained for the embodied energy associated with the processes are considerably less than those reported in Table 3. The reasons for this are not known at present.

A search of the literature for LCA of composite manufacturing has revealed the data shown in Table 6.

Table 6: Embodied energy and GWP of composite manufacture

Composite	EE (MJ/kg)	GWP (kg CO_{2e}/kg)	Reference
CF-EP	200	11.2	Rydh and Sun (2005)
CF-EP		26.7-34.5	Bachmann et al. (2017)
CF-EP	315.0	10.10	Kara and Manmek (2009)
GF-PE	169.69		Song et al. (2009)
GF-UP	11.0	1.11	Kara and Manmek (2009)
GF-PE	12.0	0.60	Kara and Manmek (2009)
GF-PE+VE	26.1	0.79	Kara and Manmek (2009)
GF-VE	26.0	1.23	Kara and Manmek (2009)
GF-VE	14.0	0.57	Kara and Manmek (2009)
GF-PE-SMC*		1.99	Witik et al. (2011)
CF-SRIM*		48.06	Witik et al. (2011)

CF=carbon fibre, GF=glass fibre, EP=epoxy, UP=unsaturated polyester, VE=vinyl ester, SMC=sheet molding compound, SRIM=structural reaction injection molding, *vehicle bulkhead manufacture

The data supplied in the report of Kara and Manmek (2009), gives EE and GWP values for GF reinforced composites that appear to be quite low, given the values reported for resins and composites reported elsewhere in this report. The data that they reported was obtained by working with five composite manufacturers in Australia and are the cradle to factory gate analyses including transportation of raw materials. Further work will be conducted to examine the impacts associated with composite manufacture.

LCA of Resins

Polyester Resin

Polyester resins are generally manufactured by the reaction of saturated or unsaturated dibasic acids, or acid anhydrides (see Appendix A) with di-functional alcohols (Appendix B). The unsaturated polyester backbone is formed by a condensation reaction of the two components. Once the polyester backbone is formed it is dissolved in a reactive diluent, for which styrene is usually used, but acrylates or methacrylates can be used in speciality resins. The resin is cured by reaction of the unsaturated polyester chains with styrene in a free-radical process, using a peroxide (e.g., methyl ethyl ketone peroxide, MEKP) initiator, plus a reducing agent (typically a cobalt salt). By varying the ratio of saturated to unsaturated di-acids, it is possible to control the cross-link density and hence the rigidity of the thermoset polymer. Over 2 million tonnes of polyester resins are manufactured per year globally. Fillers are very often added at up to 40-50% weight to reduce cost and the vapour permeability of the resin. Flake glass, or silane treated micaceous iron oxide are often preferred as fillers. The ester linkages in the polyester backbone are susceptible to hydrolysis when water penetration occurs.

Table 7: LCA data for polyester resins

Material	EE (MJ/kg)	GWP (kg CO _{2e} /kg)	Reference
Unsaturated polyester	62.8		Suzuki and Takahashi (2005)
Unsaturated polyester	63-78		Song et al. (2009)
Unsaturated polyester	110		Wang et al. (2013)
Unsaturated polyester	87.8	3.79	EuCIA
UP DCPD based	77.0	2.93	EuCIA
UP DCPD based	90.2	3.06	Rietveld and Hegger (2014)
UP isophthalic acid based	91.7	4.13	EuCIA
UP isophthalic acid based	86.9	4.15	Rietveld and Hegger (2014)
UP orthophthalic based	94.6	4.19	EuCIA
UP orthophthalic based	92.5	4.32	Rietveld and Hegger (2014)
UP maleic based	87.9	3.93	EuCIA
UP maleic based	76.9	3.11	Rietveld and Hegger (2014)
Polyester	103.8		Bath ICE database

Vinyl ester resins

Vinyl ester resins are produced by the reaction between an epoxy resin and an unsaturated carboxylic acid and are more expensive than polyester resins. Vinyl esters are more damage-tolerant compared with polyesters and are more resistant to water penetration, they exhibit less shrinking on curing and exhibit better bonding to core materials so de-lamination is less of an issue. The reduced number of ester linkages in the backbone makes the cured resin less susceptible to hydrolysis compared to a polyester resin.

Table 8: LCA data for vinyl ester resins

Material	EE (MJ/kg)	GWP (kg CO _{2e} /kg)	Reference
----------	------------	-------------------------------	-----------

VE Resin (BPA epoxy based)	121.5	5.97	Eu CIA
Bisphenol-A VE	119.3	5.87	Rietveld and Hegger (2014)

Epoxy resins

The most common commercially used epoxy resins are bis-A epoxy (bisphenol-A diglycidyl ether epoxy) and novalac epoxy (epoxylated phenol-formaldehyde novalac). Bisphenol-A is synthesised by the condensation reaction of acetone with two molecules of phenol. The products of the cumene process (acetone and phenol, derived from the reaction of benzene with propylene) can be used to produce bisphenol A.

Table 9: LCA data for epoxy resins

Material	EE (MJ/kg)	GWP (kg CO _{2e} /kg)	Reference
Epoxy	76-137	4.7-8.1	Bricout et al. (2017)
Epoxy	76.0		Suzuki and Takahashi (2005)
Epoxy	137.1	8.1	Plastics Europe (2005)
Epoxy	140.71	5.9	Joshi et al. (2004)
Bisphenol-A	80.1	2.54	Plastics Europe (2011)
Bisphenol-A	120-140	5.3-6.2	Ecoinvent
Epoxy	77.4		US DoE (2016)
Epoxy	76-80		Song et al. (2009)
Epoxy	137.1	5.7	Rankine (2006) (quoting PE)
EP Curing Agent-Ethylenediamine	124.6	6.3	Eu CIA (2014)
EP Curing Agent-Phthalic Anhydride	78.2	2.7	Eu CIA (2014)
EP Resin	135.0	6.8	Eu CIA (2014)

Styrene

Styrene was manufactured by the dehydrogenation of ethylbenzene at a temperature of 630°C in the presence of catalysts comprising zinc, chromium, magnesium or iron oxides. Because of low conversion efficiencies, the oxirane process has been adopted in modern manufacturing plants, which involves the oxidation of ethylbenzene with hydrogen peroxide, followed by reaction with propylene to produce methyl benzyl alcohol and propylene oxide. The methyl benzyl alcohol can be dehydrated at relatively low temperatures to produce styrene. Plastics Europe has published an ecoprofile of styrene production, dated 2005. This quoted an embodied energy of 82.6 MJ of primary energy and a GWP of 3.1 kg CO₂ eq. per kg of styrene. Ethyl benzene is produced by the reaction of benzene with ethylene using aluminium chloride as a catalyst. Ethylene is derived from natural gas, or from crude oil by steam cracking and benzene is produced from pyrolysis gasoline (a by-product of the steam cracking of saturated hydrocarbons), by dehydrodealkylation of toluene, or from reformat (a product obtained by the catalytic reforming of naphtha), or from light oil, which is the condensate fraction of coke oven gas obtained from coal pyrolysis. Over 60% of benzene is derived from pyrolysis gasoline.

Table 10: LCA data for styrene production

Material	EE (MJ/kg)	GWP (kg CO _{2e} /kg)	Reference
----------	------------	-------------------------------	-----------



DACOMAT



DACOMAT - Damage Controlled Composite Materials

Styrene	82.6	3.1	Plastics Europe (2005)
---------	------	-----	------------------------

LCA of Reinforcement

LCA of Glass Fibre

The most common type of glass fibre used for composites is E-glass, which is an alumina-borosilicate glass with low levels of alkali oxides. However, E-glass fibres are susceptible to chloride ion attack and are unsuitable for marine applications. Other types of glass fibres produced are R-glass, A-glass, AR-glass, T-glass, ECR-glass and C-glass. R-glass fibres are used for higher strength applications such as building or aerospace applications (these are referred to as S-glass fibres in the US). C-glass and T-glass fibres are used for thermal insulation products.

In the first stage of glass manufacture the different ingredients are accurately weighed into a mixing vessel where they are combined together in the batch house. After mixing, the ingredients are transferred to a furnace where they are heated to temperatures around 1400°C.

Differences in energy intensity (reported as MJ per kg fibre) and Global Warming Potential (kg CO₂e per kg fibre) are illustrated in Table 11.

Table 11: LCA data for glass fibre production

EE (MJ/kg)	GWP (kg CO ₂ e/kg)	Reference
19.9		US DoE (2016)
13-32		Song et al. (2009)
48.33	2.04	Joshi et al. (2004)
45.6	2.5	Bachmann et al. (2017)
21.1		Bachmann et al. (2017)
13-32		Bachmann et al. (2017)
45		Bachmann et al. (2017)
10.3		Bachmann et al. (2017)
31.6	2.16	EuCIA
28	1.54	Bath ICE database
51.3	2.95	La Rosa (2013)
20.9-37.0	1.3-2.6	Ecoinvent
	1.3-1.9	ELCD

GlassFibreEurope, the European Glass Fibre Producers Association have published the results of an LCA study of glass fibre production. The impact was mainly associated with the glass melting stage of the production process (17.1-20.5 MJ/kg and 1.03-1.44 kgCO₂e/kg).

Table 12: LCA data from the GlassFibreEurope study (GEF 2016) per kg of glass fibre

Fibre type	EE (MJ/kg)	GWP (kg CO ₂ e/kg)
Dry chopped strands	27.6	1.42
Wet chopped strands	24.4	1.23
Rovings	24.5	1.29
Assembled rovings	33.9	2.09
Mats	40.5	1.78

LCA of Carbon Fibre

About 90% of carbon fibres are made from poly(acrylonitrile) (PAN) fibre precursors, with the remainder made from rayon of pitch. Before the fibres are carbonised, they are pre-heated at 200-300°C in air for 30-120 minutes. After this stabilisation process they are carbonised by heating at 1,000-3,000°C in an inert atmosphere for several minutes. After carbonisation, the fibres may then be surface treated in order to improve bonding properties.

Table 13: LCA data for carbon fibre production

EE (MJ/kg)	GWP (kg CO _{2e} /kg)	Reference
436		Suzuki and Takahashi (2005)
247		Suzuki and Takahashi (2005)
704	31.0	Das (2011)
183-286		Song et al. (2009)
478.5	29.7	Bachmann et al. (2017)
285.9	20.5	Bachmann et al. (2017)
286	22.4	Bachmann et al. (2017)
1122	53	Bachmann et al. (2017)
286-704	24.4-31	Bachmann et al. (2017)
198-594		Pimenta and Pinho (2011) quoting Carberry (2009)

References

- Bachmann, J., Hidalgo, C., Bricout, S. (2017) Environmental analysis of innovative sustainable composites with potential use in aviation sector – a life cycle assessment review. *Science China Technological Sciences*, **60**, 1301-1317.
- Cabeza, L., Barrenesche, C., Miro, L., Morera, J., Bartoli, E., Fernández, I. (2013) Low carbon and low embodied energy materials in buildings: a review. *Renewable and Sustainable Energy Reviews*, **23**, 536-542.
- Carberry, W. (2009) Aerospace's role in the development of the recycled carbon fibre supply chain. In: *Carbon Fibre Recycling and Reuse 2009 Conference*, IntertechPira, Hamburg, Germany.
- Das, S. (2011) Life cycle assessment of carbon fiber-reinforced polymer composites. *International Journal of Life Cycle Assessment*, **16**, 268-282.
- Dixit, M., Fernández-Solís, J., Lavy, S., Culp, C. (2010) Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, **42**, 1238-1247.
- Dixit, M., Fernández-Solís, J., Lavy, S., Culp, C. (2012) Need for an embodied energy measurement protocol for buildings: A review. *Renewable and Sustainable Energy Reviews*, **16**, 3730-3743.
- Fay, R., Treloar, G. (1998) Life cycle energy analysis—a measure of the environmental impact of buildings. *Environment Design Guide GEN22*, 1–7.
- Fay, R., Treloar, G., Iyer-Raniga, U. (2000) Life-cycle analysis of buildings: a case study. *Building Research and Information*, **28**, 31–41.
- GFE (2016) https://www.glassfibreeurope.eu/wp-content/uploads/2016/11/LCA-report-CFGF-products_20161031_PwC.pdf (accessed 15/06/2018)
- Hill, C., Dibdiakova, J. (2016) The environmental impact of wood compared to other building materials. *International Wood Products Journal*, **7**, 215-219, (2016).
- Huijbregts, M., Rombouts, L., Hellweg, S., Frischknecht, A., Van de Meent, D., Ragas, A., Reijnders, L., Struijs, J. (2006) Is cumulative fossil energy demand a useful indicator for the environmental performance of products? *Environmental Science and Technology*, **40**, 641-648.
- Jiao, Y., Lloyd C., Wakes S. (2012) The relationship between total embodied energy and cost of commercial buildings. *Energy and Buildings*, **52**, 20–27.
- Joshi, S., Drzal, L., Mohanty, A., Arora, S. (2004) Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites A*, **35**, 371-376.
- Kara, S., Manmek, S. (2009) Composites: Calculating their embodied energy. Report by the Life Cycle Engineering and Management Research Group at the University of New South Wales.

La Rosa, A., Cozzo, G., Latteri, A., Mancini, G., Recca, A., Cicala, G. (2013) A comparative life cycle assessment of a composite component for automotive. *Chemical Engineering Transactions*, **32**, 1723-1728.

Lee, B., Trcka, M., Hensen, J. (2011) Embodied energy of building materials and green building rating systems – a case study for industrial halls. *Sustainable Cities and Society*, **1**, 67-71.

Pimenta, S., Pinho S. (2011) Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. *Waste Management*, **31**, 378–92.

Rankine, R., Chick, J., Harrison, G. (2006) Energy and carbon audit of a rooftop wind turbine. *Proceedings of the Institute of Mechanical Engineers Part A – Journal of Power and Energy*, **220**, 643–54.

Rietveld, E., Hegger, S. (2014) Life cycle assessment of four generic unsaturated polyester (UP) resins and one vinyl ester (VE) resins. Report by Ernst and Young LLP for AVK.

Schepp, C. et al. (2006) *Plastics Industry Energy Best Practice Guidebook*. Focus on Energy.

Song, Y., Youn, J., Gutowski, T. (2009) Life cycle energy analysis of fiber-reinforced composites. *Composites A*, **40**, 1257-1265.

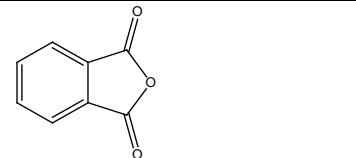
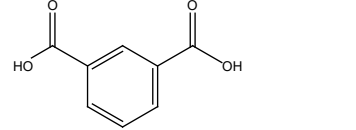
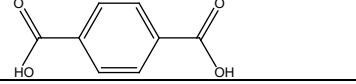
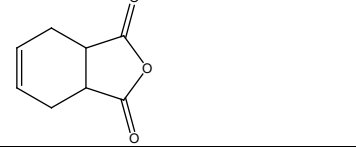
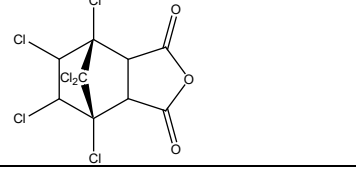
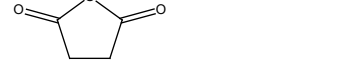
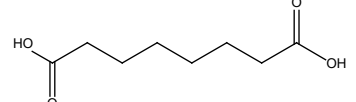
Suzuki, T., Takahashi, J. (2005) Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. *Proceedings Ninth Japan International SAMPE Symposium*, 14-19.

US DoE (2016) Bandwidth study on energy use and potential energy saving opportunities in the manufacturing of lightweight materials: Glass fibre reinforced polymer composites. *Report US Department of Energy*.

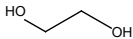
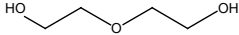
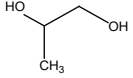
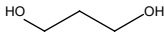
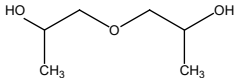
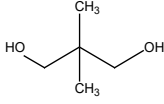

Wang, J., Shi, S., Liang, K. (2013) Comparative life cycle assessment of sheet molding compound reinforced by natural fiber vs. glass fiber. *Journal of Agricultural Science and Technology B*, **3**, 493-502.

Witik, R., Payet, J., Michaud V., Ludwig, C., Månson J-A. (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. *Composites Part A Applied Science Manufacturing*, **42**, 1694–709.

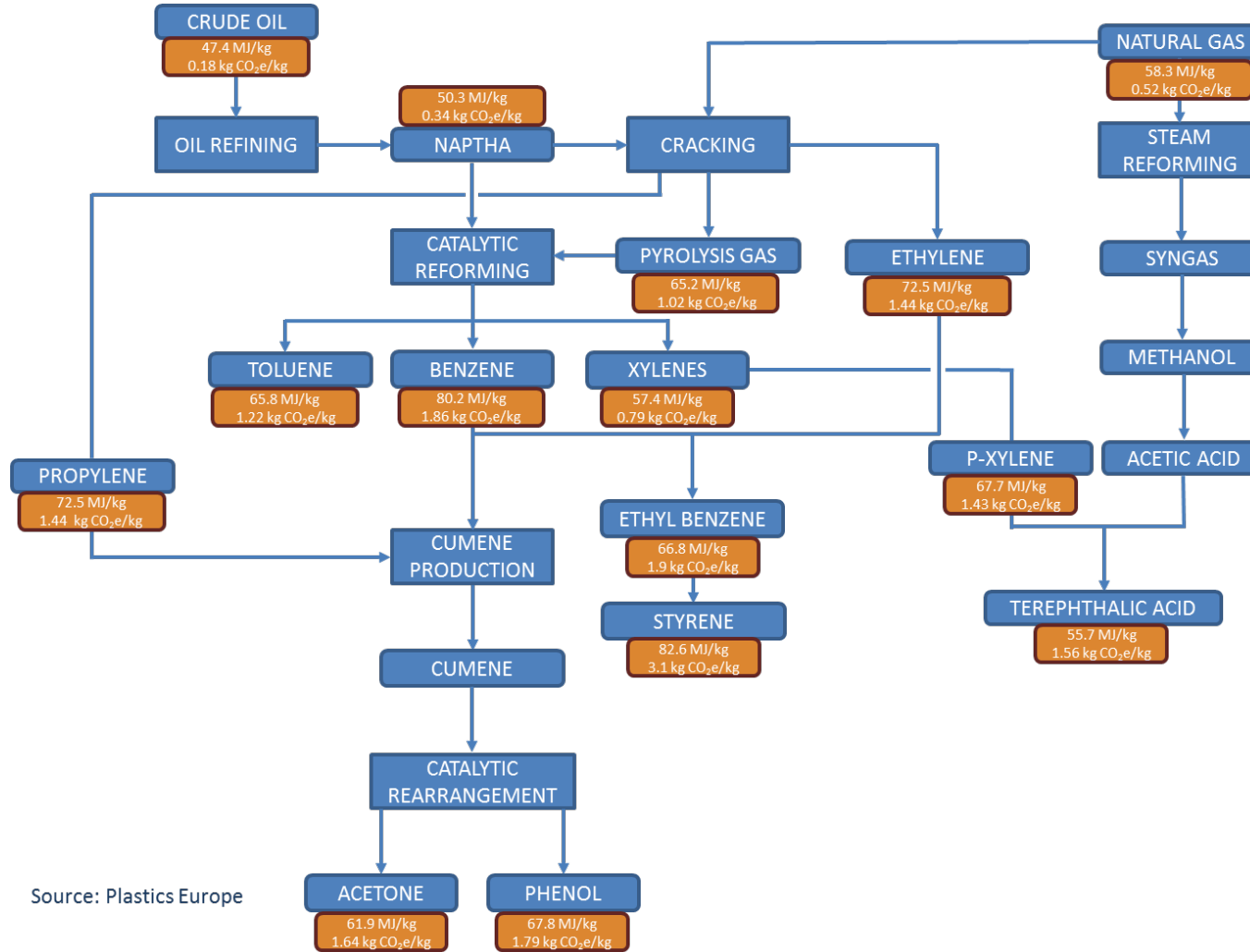
Appendix A: Some di-functional acids used for the manufacture of polyester resins

<p>Phthalic anhydride: is produced by the vapour phase oxidation of naphthalene or o-xylene in the presence of a vanadium pentoxide catalyst. The use of naphthalene as a feedstock is less efficient and is being phased out.</p>	
<p>Isophthalic acid: is obtained from meta-xylene by oxidation using oxygen in the presence of a cobalt-manganese catalyst.</p>	
<p>Terephthalic acid: is obtained by the liquid phase oxidation of para-xylene in acetic acid using magnesium or cobalt acetate as a catalyst.</p>	
<p>Tetrahydrophthalic anhydride: produced by the catalytic hydrogenation of phthalic anhydride.</p>	
<p>Hexachloroendomethylenetetrahydrophthalic anhydride: produced by chlorination of phthalic anhydride. Is used as an ingredient in fire-resistant polyesters.</p>	
<p>Maleic anhydride: can be produced from an butane/air mixture in the presence of a vanadium-phosphorus oxide catalyst.</p>	
<p>Adipic acid: is produced from a mixture of cyclohexanol and cyclohexanone by oxidation with nitric acid.</p>	

Appendix B: Some di-functional alcohols used in the manufacture of polyester resins

<p>Ethylene glycol: also known as monoethylene glycol (MEG) is a diol used for the production of polyester and poly(ethylene terephthalate) (PET) resins. MEG is obtained by the hydrolysis of ethylene oxide which is in turn made by the oxidation of ethylene. Avantium, based in the Netherlands, have plans to build a pilot plant to produce bio-based MEG directly from sugars. Previously, the route to bio-MEG involved a four-step process, making the product uneconomic. Avantium have developed a one-step hydrogenation conversion process with high carbon efficiency.</p>	
<p>Diethylene glycol: derived from ethylene glycol by a condensation reaction.</p>	
<p>Propylene glycol (propane-1,2-diol): is produced by the acid catalysed hydrolysis of propylene oxide, which is obtained from propylene by the hydrochlorination route, or by direct oxidation.</p>	
<p>Propane-1,3-diol: is produced by Shell from ethylene oxide via hydroformylation to 3-hydroxypropionic aldehyde in an 83 ktonne p/a production facility in Geismar, Louisiana. PDO can be used as a precursor for the polymer poly(trimethylene terephthalate) (Kurian 2005). Propanediol can be produced by fermentation of glycerol (Glory Biomaterial, Shenghong Group, METEX, Technip). Metex has announced plans for a 47 ktonne per annum plant to produce PDO for the cosmetics market. Dupont and Tate and Lyle have developed a process to manufacture PDO from a glucose feedstock located in Loudon TN USA with an annual production capacity of 63.5 kt, which they claim has a cradle to gate GWP 56% lower than the petrochemical route. PDO is a component of industrial bio-polyesters, where it is combined as a co-monomer with terephthalic acid or dimethylterephthalate for the manufacture of poly(trimethylene terephthalate), such as DuPont's Sorona®, CPD Natureworks®, or Shell's Corterra™.</p>	
<p>Dipropylene glycol: derived from propylene glycol by a condensation reaction.</p>	
<p>Neopentyl glycol: is produced by the reaction of isobutyraldehyde and formaldehyde in the presence of an alkali catalyst to produce hydroxypivaldehyde which is subsequently hydrogenated to produce neopentyl glycol.</p>	
<p>Hexane-1,6-diol: is produced by the hydrogenation of adipic acid.</p>	

Appendix C: Process chain for platform chemicals leading to resins





DACOMAT - Damage Controlled Composite Materials

Appendix D: Process chain for epoxy resin production

