EPSRC FUTURE COMPOSITES MANUFACTURING RESEARCH HUB

UK Composites Research Challenge Landscape Report – Composites Sustainability

Abstract

A research-driven roadmap for future composite manufacturing development covering the outputs of 3 workshops identifying key challenges for academia

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Foreword – Nick Warrior, CIMCOMP Hub Director

It is a pleasure to introduce the second set of outputs from the Hub's UK Composites Research Challenge Landscape covering the topic of composites sustainability. The weight-saving advantages of composites are well known, but increasingly, the focus has widened to include concern for the end of life disposal, carbon emissions during the production phase and circularity. Since the launch of the Hub in 2017, we have had a keen interest in identifying where the challenges for the future of composites manufacturing lie. This exercise aims to bring an academia-led view of the challenges highly complementary to existing roadmaps.

This document concludes the second in a series of landscaping exercises looking at fundamental research challenges for composites manufacturing from an academic, low Technology Readiness Level perspective. This study represents a significant resource for the UK composites community, recording and analysing almost 500 fundamental challenges in composite manufacturing science and technology. We hope that these data help the community to address the sustainability challenges within composite manufacturing better, and improve the quality, cost and lifespan of current and future composite parts.

Finally, I want to express my thanks to those from across the community who have given up their time to engage with the Hub in the preparation of this document.

Prof. Nick Warrior - Director

With thanks to all contributors without whom this report would not have been possible.

Introduction

The EPSRC-funded Future Composites Manufacturing Research Hub is a key player in funding fundamental composites manufacturing research in the UK. The Hub Sustainability Workshop Series aim to develop a process for identifying and validating fundamental research challenges for composite manufacturing to be addressed within the next ten years. This will enable the Hub and the broader composites community to remain current with research trends and fund the most critical and timely research.

It is envisaged that the data collected, and the analysis contained herein will play a key role in:

- Informing future funding decisions and shape calls for Hub Feasibility Studies
- Ensuring that Hub research themes remain relevant
- Identification of areas of research synergy between technology areas and Hub projects
- Underpinning knowledge & technology transfer into the High Value Manufacturing Catapult (HVMC) Centres
  Justification of resource needs for research projects

Scope

The concept of Net Zero has become synonymous with future manufacturing and commercial industry across all sectors, and our work in fundamental composites manufacture will embrace the key values therein but extrapolated to cover the intricacies of both our own research needs and those of industry for whom the below information has been collected and corroborated.

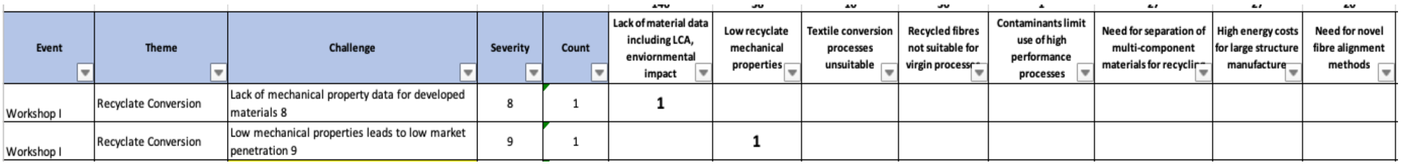
Therefore, the following sustainability-led challenges within composites manufacturing and consequent challenge sub-themes will fall into industry/academic identified 'Grand Challenges':

- Zero Prototype – Validated high-fidelity predictive process simulations of key manufacturing technologies.
- Zero Inspection – Studies in in-process sensing and prognostics plus through-life monitoring for non-destructive testing and product service life extension.
- Zero Waste – Incorporating recovered and recycled materials from in-process scrap and end-of-life structures into new high-performance components.
- Zero Touch Labour – Automation, robotics and robotics in key composites manufacturing processes: fibre deposition, cutting, pick-and-place, material handling and tooling preparation.
- Zero Tooling – Tooling strategies across the range of length scales and production volumes including novel, flexible, reconfigurable, and recyclable tooling innovations and additive manufacturing for tool-less composites.

Methods

Data Collection & Reduction

Sustainability challenges were captured through a series of meetings and workshops ranging from 2019 to 2022 with HVM Catapult engineers, academic staff, and industry leaders. A peer-reviewed literature review spearheaded the sustainability challenge data capture exercise (Sustainability Workshop I) by external sustainability experts to identify an initial series of manufacturing process challenges – 186 challenges – to form the basis of discussion with the wider composites community. Though some of these challenges were not specifically sustainability-focused, they gave a solid framework to build upon with subsequent workshops and discussions. The subsequent Sustainability Workshops (II and III) identified 274 further challenges. A spreadsheet was compiled with all 460 challenges, and a series of 'sub-themes' was created based on the nature of the challenge, e.g., "Waste materials often not in the same form as input materials" created the sub-theme "Need for separation of multi-component materials for recycling". Any other challenges with this general sub-theme would have a 1 in its column.



Event	Theme	Challenge	Severity	Count	Lack of material data including LCA, enviornmental impact	Low recyclate mechanical properties	Textile conversion processes unsuitable	Recycled fibres not suitable for virgin process	Contaminants limit use of high performance processes	Need for separation of multi-component materials for recyclin	High energy costs for large structure manufacture	Need for novel fibre alignment methods
Workshop I	Recyclate Conversion	Lack of mechanical property data for developed materials 8	8	1	1							
Workshop I	Recyclate Conversion	Low mechanical properties leads to low market penetration 9	9	1		1						

This process was then repeated for all 460 challenges. Some challenges fit into several sub-themes, leading to 1,191 categorisations for the challenges.

Results

Landscape Analysis Workshop (Sustainability Workshop I) 2019

Challenges were suggested by contributors and ranked on a 10-point severity scale. This ranking is intended to identify the urgency with which they should be addressed, where 10 represents a significant pain point which requires critical attention and 1 represents the least severe and hence the least necessary to resolve in the short term.

Challenges were identified based on five headings – recyclate conversion, lifecycle analysis, waste reduction, fibre recovery, and disassembly. These challenges were then further categorised into a series of sub-themes.

Raw Data - Recyclate Conversion

Challenge	Severity
Lack of mechanical property data for developed materials	8
Low mechanical properties lead to low market penetration	9
Low fibre packing for fluffy random fibres	10
Textile conversion processes not suitable for low strain to failure fibres	4
Few processes available for conversion	6
Recovered fibre formats not suitable for virgin fibre manufacturing processes	8
Residual char and other contaminants limit use of high performance processes	5
Multi-component materials ~ recyclable as is or requirement to return to separate constituents?	
Energy requirements and optimum process for reduction of WT blades and boat hulls for transport?	
Loss of fibre length, loss of strength of glass fibres and loss of surface treatments (coupling agents) in the recycling process?	
Continuous remanufacture of rCF products	8
Retention of rCF length	4
- Separating mixed fibre recyclate (either mixed materials or mixed material grades)	3
- How to resize fibres (glass and carbon)	5
- Novel alignment methods	5
- Assessing minimum quality standards needed for recyclate to be used in different secondary applications	8
- Alternative methods for analysing recycled fibres (particularly glass) outside of SEM and SFTT. These processes are very difficult with recycled fibres and particularly recycled glass	6
Finding markets for recyclates which may be lower quality than the feedstocks	8
Separation of different materials from complex composite structures such as wind turbine blades	7
Shredding and downsizing of large structures	10
Recycling infrastructure needs to keep pace with evolving technologies e.g., carbon fibre blends in turbine blades	6
Creating aligned rCF veils and/or tapes that are usable in manufacturing processes, e.g. ATL and achieve high FVF	9
Trialling aligned rCF in composite applications to establish design parameters and identify the applications where they will find the most benefits (e.g. where high tow shearing is needed)	8

Creating fabrics from rGF, probably thermally recovered from fluidised bed (in conjunction with development of Strathclyde process), possibly pyrolysis, but also perhaps with fibres separated from regrind. Fabrics need to meet manufacturing requirements in terms of mechanical properties, aerial weight tolerances, usability in one or more of: hand layup with roller; hot press with thermoplastic; Baypreg or Hennecke type process with thermoset as used in automotive interiors; vacuum infusion	9
Aligned rGF from fluidised bed, e.g. for wind turbine blade skins, automotive exterior panels	5
Separate out matrix from fibres, applicable for thermoset and also thermoplastic matrix composites	9
Retain fibre length as long as possible/retain continuous fibres as they are	9
Bring alignment/directionality in recycled/recovered short fibres in their new composite application	7
How to ensure a strong interface with recovered/recycled fibres	6
Fibre length and alignment	
Uses of degraded resin not addressed	
Lack of products and testing data	
Lack of standards relating to a recycling process - is re-sizing needed?	
Supply chain fragmented especially for GFRP	
GFRP limited to grinding or fluidised bed pyrolysis. These technologies have limitations. Development of new tech needed. I'm excluding cement kiln as this is not a recovery process	
Recovery of mechanical properties close to virgin fibres	8
Development of additional mechanical or functional properties superior to virgin fibres	9
Formatting of the recycled fibres into product forms acceptable to industrial users	7
Formatting of the recycled fibres with directional alignment for higher performance applications	9
1. The current research are mainly focusing on the material performance improvement or functionality development with less consideration of production rate of conversion process and its energy costs, environmental impact, commercial viability. Though we are doing lower TRL research, a reliable evaluation of the factors maintioned before should be required for any project under the manufacturing theme.	10
2. For composites manufacturing with virgin fibre material, much efforts have been spent on understanding manufacturing parameters. However, the recycled fibre material always has different format comparing to the virgin one. Lacking understanding of the effects on manufacturing process/parameters when using recycled fibre material, will lead to a significant negative impact on its routs to the market.	10
3. Recycled fibres has its discontinuous format inborn. Instead of making its performance competitive with continuous virgin fibre material, it is worth to explore the benefits of short fibre products.	7
Recycled Carbon/glass fibres and thermoplastics composites for automotive applications	
Recycled carbon/glass fibres for wind turbine blades	
Cost	5
Acceptability of the technology	4
Quality of fibres	10
Uniformity of the fibres	10
Certification	8
Composite (containing these short recovery fibres) processing	7
Long fibre handling and reprocessing	10
Recovered fibre chopping and sorting	9
Fibre length consistency	9
Fibre realignment and volume fractions achieved	9
Applications	10

Raw Data - Lifecycle Analysis

Challenge	Severity
LCA based view not widely accepted	5
Lack of data for real processes	9
Availability of generic data gives false impression of accuracy	3
Complex software requires lots of knowledge	8
Availability of validated software and data?	
Consistent methodology for the acquisition of validated data?	
Standards to define setting goal and scope including allocation of environmental burdens to by-/co-products?	
Agreed routes to choice of proxy alternatives when chosen material grade lacks data set?	
Checklist of what should be considered in the LCA across the range of composite materials (ISO14047 burdens or Azapagic environmental impact classification factors, and BS8905 land use, or categories in e.g. GaBi/MarineShift360/RECIPE/SimaPro, etc.	
vCF LCA database is lacking (environmental and cost data) (confidentiality related)	9
Establishment of standards for CF recycling	8
LCA data related to collection, separation of different types of CFRP waste and transport of waste related to recycling plant locations is lacking	6
Alternative renewable precursor materials (e.g., lignin) versus PAN-based	6
Life cycle material supply chain analysis	6
Affordable LCA database related to CF recycling and reuse	5
- Creating a baseline product environmental footprint category rule (PEFCR) for different intermediates	8
- Filling the gaps in CO2e for composite materials	9
- Highlighting the policy gaps and conducting impact assessments to understand the potential if solved	3
- Avoid treating recycling like a black box! Build proper models that incorporate losses	4
Completeness of assumptions used to compile LCA	
Lack of data available	
8/10 There is a general lack of consistent LCA data in composites - in particular with Carbon fibre production and bespoke resins (especially bio-based). EPDs and the like are required if fair real life comparisons are to be made.	8
7/10 Many of the recovery processes explored are at lab or pilot scale and thus are very inefficient compared to established industrial processes. As such the potential of such low TRL recovery/recycling is often missed when LCAs are applied without any extrapolation to industrial scale.	7
Veracity and transparency of LCA sources, and their standardisation	10
Understanding how LCAs should be used and interpreted by stakeholders and policy-makers	5
Not sure which of these count as low TRL research.	

Need industry guidance on LC assessment and development of product category rules appropriate for composite parts.	8
Awareness in academic community that carbon fibre impact data in literature is generally far too low. If CF manufacturers still refuse to release data, then there needs to be a first principles approach to development of impact data for CF, which Nottingham has already done some work on, followed up by EuCIA and Aachen. I'm not up to date on this, possibly NCC is, but there needs to be a suite of data for different classes of CF. (i.e. 1k tow is much higher impact than 50k tow.)	10
Erroneous data in ICE database for FRP should be removed or replaced with a suite of realistic data, e.g. from EuCIA EcoCalculator, and the various carbon calculators which use ICE database should be revised to suit. (10, but not research)	10
A review of impacts of solvent based CF recovery processes, as those done in 2015/16 were predominantly based on lab data, so not representative. Perhaps this exists (please send me if it does!)	3
Lack of robust data at commercial scale. Recycling techs are generally low TRL except pyrolysis for CFRP	
Capture of relevant & accurate environmental impact data for the recycling & fibre recovery processes	5
1. Lacking reliable database (contains energy cost, production rate, capable waste stream, products properties) for recycling and reuse technologies. So LCAs contain lots of assumptions can not provide objective and reliable analysation.	10
Manufacturing and testing of the above mentioned case studies	
Decoupled from supply chain management / process modelling	10
Decoupled from core chemical engineering (especially since chemical engineers are the only disciplines good at process design!)	10
Data availability for materials, processes and consumables	10
Info sharing across a supply chain	8
Industry appreciation of LCA benefits and limitations	9

Raw Data - Waste Reduction

Challenge	Severity
Cost of separation limits desire to collect in-house waste	5
low bulk density of waste materials increases costs	6
Diversity of input materials makes identification of exact materials complex	8
Waste materials often not in the same form as input materials	8
Time and space requirements for collection of waste	7
Few collectors / processors of waste reduces motivation to collect	9
Very low value of waste materials	10
Markets for waste streams (e.g. prepreg CFRP to mould tool manufacture or jewellery sector) within a circular economy?	
Substitution of prepreg with LCM processes so waste stream is constituent, not agglomerated, materials	
- Increasing the efficiency and effectivity of pattern cutting	4
- Creating software (and hardware) that can be used to identify offcut shapes (and orientations). And the other end of it, where there's a server that is coded to interact with CAD to identify possible matches between available scraps and new products	7
- Re-lifing scraps	3
lack of infrastructure to facilitate effective recycling solutions, lack of technological maturity,	
How to make scrap recycling cost-effective and easy for small manufacturers	7
A review of composite manufacturing processes to understand resource and energy efficiency through the supply chain, identify hotspots that could be improved. Tow to part processes (e.g. FW, pultrusion, automated tow placement) should be inherently better, but this needs to be clearly communicated to inform design.	7
Process for GRP roofing sheet that doesn't involve cutting off 10% at the edges	8
Mould tooling to reduce scrap	7
Raising awareness that most scrap is from process errors or wrong orders, rather than inherent to the process, and developing processes to reduce / eliminate that. (Quality control, skills assessment, customer communications, etc)	5
Align prepreg manufacturing with the product design/shape/mould tool	9
(Custom made prepreg/dry fabric)	
Re-use process scarp efficiently for value-added products	9
Finding applications for in-process scrap & production waste (especially once cured)	6
Creating a database of properties enabling the wider exchange and sale of scrap for use in other processes	5
Designing processes to be more automated and inherently less wasteful	6
Use of the process scrap and thermoplastics composites	
waste management - planning ahead of manufacture	10
ply cutter selvage waste minimised through symbiosis of production	9
reuse with minimum processing into other products (i.e. tools)	9

Raw Data - Fibre Recovery

Challenge	Severity
High energy use of recovery processes	8
Composites are highly abrasive - need special size reduction processes	6
Lack of markets for recovered fibres	10
loss of fibre length and format during process	8
Fibre mechanical property reduction	5
Lack of markets for by-products of pyrolysis or solvolysis processes	2
Lack of competition in recovery market - sole UK supplier	7
Recovery of fabric reinforcements by deplying?	
Processes for glass fibre that do not degrade strength?	
Maintenance of fibre surface coating/size/coupling agent (normally removed by recovery processes)?	
Low energy-intensive thermal recycling	6
Techno-economic analysis of different recycling processes at different TRLs	8
Recycling plant location and capacity optimisation	5
- New techniques for fibre recovery	10
- Methods for recovery that don't burn off the matrix	10
- Activation agents/swelling agents etc. that can increase the efficiency of recovery	8
Dismantling and downsizing of large composite structures such as wind turbine blades	10
Development of U Strathclyde fluidised bed + post treatment for GRP	

Supply chain and business case analysis, including interviews with waste management organisations and cement companies, to see how it could be economically viable to create a GRP to cement kiln recycling process in UK - depends on having the right equipment for shredding GRP in the right locations to minimise transport costs, and finding a business model which can incentivise the necessary investment. In the longer term, the most suitable waste could be diverted to fluidised bed.	9
Solvolysis which actually gains something useful from the chemical soup?	7
Understanding what happens during a CFRP pyrolysis recycling process if carbon nanotubes are incorporated in the composite (7, or 10 if CNTs are going to be used a lot more, but perhaps not)	7
Solvolysis and pyrolysis do not recover degraded resin products. Viability of their recovery is only just being considered. Techno-economic analysis indicate this is viable. Further research is needed.	
Solvolysis only demo at large lab scale. Process is scalable but will be semi-continuous. Seems to be growing interest in this process.	
Data largely based on homogeneous clean manufacturing waster. This needs to be moved to heterogeneous dirty end-of-life material to have real impact	
Optimising pyrolysis and solvolysis processes to satisfy recycled fibre property needs and economic processing requirements (throughputs, costs, ability to handle range of wastes etc)	7
Creating solvolysis processes with benign chemicals to avoid HSE risks whilst maintaining process performance	9
Ability of recycling processes to handle all potential composite waste types economically	8
Identification of materials	8
Comminution stages to handle materials	5
Separation of mixed materials	8
Fibre damage incurred in reclamation	7
matrix recovery	10
scale	9
business model	9

Raw Data - Disassembly

Challenge	Severity
Large structures require lots of space and bring transport complexity	6
Lack of automated processes for initial size reduction	7
multi-material & hybrids increases complexity of disassembly	6
Lack of models for composite fragmentation in comminution processes	8
Difficult to identify parent materials or fibres & resins	8
- Reversible joining techniques	7
- Policy around decommissioning	9
7/10 Efficient recovery (collection transportation etc) of composites is costly and relatively high impacting when end of life materials are considered due to their wide ranging application. even larger scale uses such as wind turbines are limited. getting over the cost to recover and a market for the recovered composite or fibres is needed to ensure it happens.	7
Need to incentivise life extension, repair, reuse and repurposing before recycling	10
Design for decommissioning	8
Effective high performance disbondable adhesives, and an understanding of why these haven't yet proliferated in the supply chain	7
Automated disassembly based on a through life digital twin for automotive (and other sectors) where material content of parts is recorded at manufacturing and replacements recorded maintenance. Broader than composites, and disruptive to supply chain, but needed to retain best value of materials	10
Getting rid of those rivets in CF aircraft structures - which depends on certification of NDT techniques for kissing bond detection, and suitable environmental degradation datasets.	10
Widespread understanding at design stage of the ways in which things will be disassembled and recycled at EOL	9
Design for disassembly	7
Separation without substrate damage (replacement parts)	8
Safe disbonding mechanisms	9
Hybrid disassembly mechanisms	6
Separated part identification at End-of-life	5
Disassembly of thermoset parts-use of reversible adhesives/thermoplastic joining layers	6
(Still the problem of non-recyclability of thermoset parts remain)	
Designing the end-of-life use/reuse is important at the very start of the manufacturing the product	9
Cost effective down-sizing of large composite structures (such as wind turbines)	9
Cost effective recovery of all the different material streams enabling optimum recovery of valuable components	8
Design parameters and guides for composite parts & structures enabling easy disassembly at end of life	7
Impact of different joining techniques (especially chemical adhesives) on disassembly processes	9
Viable alternatives to high energy mechanical shredding	8
separation of assemblies (i.e. fastner removal, sealants, paint adhesives....)	9
separation of mixed material within laminates	10
cost effective disassembly	10

Data Reduction - Categorising identified challenges into sub-themes and their frequency

Sub-theme	Workshop I
Lack of material data, including lifecycle analysis data and environmental impact data	34
Lack of and validity of process data	8
Lack of composites standards and ways to analyse recycled fibre properties	8
Lack of lifecycle analysis education	
Need for economic analysis of processes	2
Challenges with the implementation of automated manufacture	3
Low/non-existent market acceptance of recycled components	12
Low mechanical and physical properties of recyclates	20
Recycled fibres are not suitable for virgin processes	12
Fragmented supply chain	8
No incorporation of waste management into the manufacturing design stage	15
Poor integration of all process steps leading to bottlenecks	1

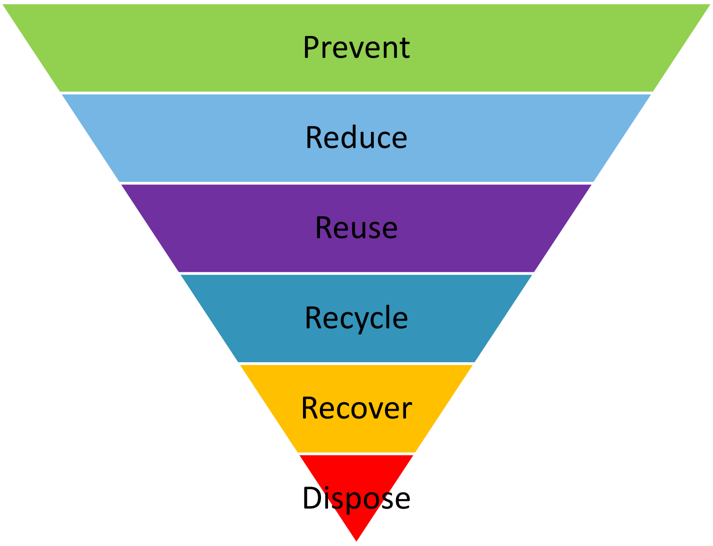
High costs involved in recycling processes	13
Non-optimal pattern cutting and mould tooling	5
Need for better separation of multi-component materials for recycling	16
High energy costs for large structure manufacture	10
Need more effective ways to analyse recycled fibre properties	2
Need for increased use of additives/alternative materials to increase recovery efficiency	11
Lack and validity of available software for design and process simulation	6
Need for more natural fibres/resins in the manufacturing supply chain	
Dismantling and demanufacturing of large structures	15
Need applications for recycled resins	7
Complexity in recycling methods, e.g., thermoplastics	
Need for novel fibre alignment methods	7
Skill gaps in process equipment and design software	4
Recycling infrastructure not suitable for large structures	10
Need for reversible joining techniques	9
Need for out-of-autoclave processes and reduced energy use in curing	
Reuse or negation of tooling	
Need for further optimisation of resins	
Need for scalability in recycling processes	7
Lack of remedial repair methods	
The low value of waste materials	3
Challenge of recycling glass fibres	
Need for more effective knowledge transfer from other sectors	
High cost of consumables	
Need for better translation of industry need to academic research	
Optimise or remove the need for freezer storage of prepreg	
Lack of competition in the UK recycling market leading to poor market traction	1
Risks involved in recycling processes (solvolysis/pyrolysis) need to reduce for wider adoption	2
Significant time and space requirements needed for waste collection	4
Need for upcycling of end-of-life components where recycling is not applicable	

Landscape Analysis Workshops (Sustainability Workshop II and III) 2022

The process by which data was captured and subsequently analysed differed from the initial challenge identification outlined above.

The below diagram illustrates the opportunities in composite waste management, indicating that prevention and reduction of virgin materials, energy consumption, and in-process scrap needs to be the highest priority. Below prevention and reuse is the need for repair, improved damage sensing, upcycling and direct reuse in composites. Further down is the opportunity for recycling of end-of-life composite components, presenting challenges in the many resin and fibre separation technologies and problems with waste format and how it can be reused. Next is recover. Composites have high calorific value and there are opportunities for glass use in cement production as an example. Finally, and what should realistically be the least frequent waste process is disposal. It is increasingly difficult to dispose of end-of-life composite parts due to high landfill costs and restrictions. It is worth noting, however, that a 2013 EuCIA study highlighted the effectiveness of incineration of end-of-life turbine blades.

The second sustainability event, held at the NCC in March 2022 (Sustainability Workshop II), provided an open discussion between academics within the Hub to voice the challenges relating to sustainable manufacturing through a series of smaller 'break-out' sessions. Challenges were identified based on four key themes – recycling methodologies, lifecycle assessment, sustainability in composite manufacturing processes and composite design and manufacturing with sustainable materials. These challenges were then further categorised into a series of sub-themes.



Raw data - Recycling Methodologies

Challenge
Willing to compromise in use phase to minimise -vs EoL phase
Market and economic analysis of recycling methods to look at segmented differences
Methods of cutting discontinuous fibres
Avoid EOL . - Repair -Increase life
Compare reclamation technologies - Similar conditions, timescales /limitations on materials
Systemate Assessment of market potential of recyclate - Design for reuse - steer regarding new material development
Material passport v important for recycling of thermoplastics
Effective meant of resizing discontinuous fibres
Recycling of thermoplastics not as easy in practice
De-risk adoption - Decrease in process barriers, -Increase in manufacturability and performance
Grading and classifying recycled fibres eg) mechanical performance, fibre length, fibre surface
Cutting discontinuous fibres to consistent fibre length distribution for specific processes
Not enough rigour in data on recycling -EE in phases improve quality of data for LCA
Fibre reclamation processes that produce a narrow and consistent range of fibre lengths
Recycling of bio-based composites - how? -what do we get out?
Design & EOL   -Data on materials - Classify -Define EOL route for each option
Fibre length -Surface quality -Sizing /Treatment
Metric recyclability of constituents - fibres, resins…. Economics, performance
Challenge manufacturer -right to repair return to manufacturer re use obsolescent design
Produce fibres at 2mm length(characteristic length)
Data on recycling -environment -cost - rate
Lower energy glass recycling - business case
Evaluate environmental impact of recycling
Passport (digital) good for wind turbines not so good for individual car parts (block chain)
Evidence base for regulation 'statistical bases'
Drive towards 'the right' fibre constituents to retain value
Reformulate glass fibre - constituents - different challenges in identifying formulation
Generalisation of material pallet
Vitrimers
Designing the right EOL strategies for different categories of virgin products - should we recycle bio-fibres?
Lego composites
What are the driving variables in recycling process design?
Circular supply chain
Design for 'Application chains' across sectors
Better control & process
Translation of industrial need into academic questions
Validity of recycling sustainable composites? (based on natural sourced resins &fibres)
EOL strategy for natural fibres & biobased resin
Yarn spinning of RCF
Glass more important challenge than carbon (volume increase, value decrease)
The right process matched to component and material
Skills of translating a challenge into a 'PhD-ready topic'
How do we manage 'additives' eg) FST or Real situation eg) paint
Address performance loss
Is it the best idea to use continuous fibres in 1st life? Chopped in & chopped out
Recycling -Variability &design data & modelling confidence & Reversible better than pyrolysis and salvaged. Application usability - degradation

Raw Data - Lifecycle Assessment

Challenge
Don't see a specific research challenge in LCA, more that this needs to be used to drive other topics
Environmental / performance impact vs Functional performance
Remove EOL stage - increase life of component
Difficult to get data accredited methodology
Round robin exercise of LCA
Better education for engineers on LCA & frameworks
How to drive design by interpreting LCA & wider impact data
The LCA challenge is to (for example) halve the embodied emissions in the current fleet of composite resin systems
Global independent body for assessing LCA data
LCA -Standardisation -Which metrics?
Life' design data eg) how much longer can a cf carbon airframe last compared to Al?
Standardisation of LCA data and credibility
Good research practice for academic projects to include energy consumption etc as data
Defining the right metrics for total life cycle impact in operation & manufacture
Increasing life by improving repairability (reducing cost)
Primary sources of data like MSDS & LCA chart
Applying uncertainty quantification to deal with variation & uncertainty of LCA data
Standardisation of research methodologies
LCA Process. Data is poor or unreliable & all is included. Data is secret. Better data OR official data
Audit of companies generally data for LCA
Why lightweighting for EV & H2 vehicles? Will future mobility change need for composites?
Industrial Policy - Energy data sheet should be provided similar to regulations for MSD's
Evidence basis for setting boundary conditions for LCA within value /user chain
Conservative allowable for LCA reporting as standard, similar to A basis / B basis rather than salesmanship
Multi-objective - considering functional life cycle, & extending use phase
Circular economy is more than just recycling
Primary data from material suppliers

Unification of data standardisation of LCA
Consider broader range eg) environmental impacts
Need sector relevant case studies with scaled LCA data - not just materials but in whole system
How do you intelligently use LCA - chasing big numbers?
Scale up from Lab to industrial assessment
Develop an ncap type organisation to hold LCA ground truth data
How do we have confidence in the measurement to drive sustainability?
Need primary measurement capability & published data
Auditing /Legislation / Regulation - Trust in LCA
Grant reviewer understanding of LCA -educating reviewers
Regulates requirement to have EPD for materials & products
LCA scenarios eg) 50,000 mile use for a car or 200,000 miles (or alter parameters)

Raw Data - Sustainability in Composite Manufacturing Processes

Challenge
End of life tooling
Bio-based tooling material
Zero defects - zero waste digital twin-surrogate models. Process monitoring - Interventions
Reduced energy consumption during manufacturing out of autoclave - oven - out of oven?
Produce standard process for measuring the energy consumption of an individual composites manufacturing process
Produce on the fly instrumentation to determine energy use of individual process methods eg) AFP
What is the wastage for different processes?
Laser cutting for really quick cutting (enables cutting of in-process waste)
Finding high value applications for discontinuous fibres
How to unravel reclaimed RCF?
Round robin to establish energy footprints of each of the composite manufacturing processes eg) AFP round robin)
Near net shape - beware of over engineering to achieve net edge
Modular reusable & recyclable tooling
Remove freezer storage request -increase shelf life
Forming simulation -So you don't need to use excess material
Process ________________cannot be untangled - border scope for next Hub - material innovation and manufacturing process innovation
Finding the right heat source for the right material
Energy efficiency manufacturing. -Heated tooling -Less metal (less thermal sink) -Adaptive
Sustainable route to bis A replacement
Consumables wastage in composites infusion process is excessively high
Thermal input -isothermal
Avoid opening doors of oven and autoclave
Business model, impact on ownership of waste
Manufacturing -temperature, dividing energy consumption - low temperature process
Presence of defects - ability to repair localised reinforcements on site repairs? (turbine blade) -Out of auto-clave
Resin which do not require external energy to cure and yet they exhibit great properties
Sustainable consumables (multiple uses)
What is the next step after OoA? Reduce power
Post env time reduce?
Focussed energy (instead of oven autoclave)
Tool heating. Low waste processing - Net shape. -Low energy curing- Processing ______waste?
Process simulation and individual process simulation - understand process robustness
Storage needed / requirement &supply chain for prepreg storage. -Prepreg stable at ambient T.
Get microwave cure to work in wider industrial application
Waste identification & pathways to reuse eg) selvedges testing
Reduced cycle cure time
Post -moulding operates -cutting holes
Regulation for cost of waste, free market economics
Renewable process-virtual space (modelling) & testing on factory floor
Reduction, Reuse, Recycling - of consumables
How to you make things last forever & modular so it can be re-certified for next application?
How to deal with 'bad product'? -usable in lower grade application?
Adaptive tool or modular. Vitromeric, remouldable composite tooling.
Efficient heat sources for curing. One piece of equipment with multi-functionality (multi-band, frequency, power)
Dismantle structures and re-assembly
Prepreg with room storage temperature
Focus on natural fibres & natural resins
Reduce need for consumables in manufacturing
Bio-based consumables?
Mould -tool costs mvov-global footprint
Reduce cure time
Lower energy processing
Sustainable tooling and consumables
Novel use of manufacturing waste

Raw Data - Composite Design and Manufacturing with Sustainable Materials

Challenge
Reformulate bio resin to be compatible with manufacturing requirement
Design service life to maximise environmental benefit in specific application
Statistical design for discontinuous fibre materials
Modular design - separability - Design optimal -Functional performance - Disassembly -Processing

How does cost change when handling & manufacturing with sustainable materials?
-Finding new (and right) applications for sustainable materials -Not simply try to replace the virgin materials of the same way
Rethink characterisation methods to allow adoption based on advantages eg) out of plane for 3D geometries
Environmental design of specific applications & environment
Tools for identifying best approaches for local reinforcement of sustainable composites with higher performance materials
Hybrid composites: bio & traditional Design based on loading scenarios
Design for disassembly - challenges? How? EOL- disassembly!
Need to be able to handle recycled fibre -current manufacturers not set up to do
Process guides for different fibres & resins used in processing
How do we avoid drop in replacement & instead design with sustainable materials to deliver function, not just replace
Sustainability - reducing mass of complex structures optimising layup with new technologies (3D printing /AFP) and optimal stress trajectories ie) open holes
How do you balance manufacturing risk &material impact to deliver overall sustainability
Design/manufacturing for reuse. -Life cycle 1/2/3 - degradation of properties, metrics /quality
Sun ovens
bio-degradable polymers a good solution? LCA of different options
Re-lifting of out of life materials
Prediction models for actual recycled formats /variables
Database on knockdowns of composite materials for recycling methods
Need process guides
Verify materials are 'drop-ins' solutions -are changes needed to manufacturing processes?
Bio-based bisphenol A & sustainable monomers
Room temperature storage
How sustainable the material is? Properties requirement of materials (resin, fibre) Sustainable manufacturing in fibres
Room temperature storage
Durability over service life
Design & manufacture for recycled materials
Non-uniformity of thermoplastics used -makes re-manufacture through melting & reforming challenging
NDE methods to fingerprint a discontinuous recycled preform. We need this info to drive the simulation
Flax or natural fibre variability. Design ranges in there materials?
How to design first life product for second life
The science of 'design for 1st,2nd,3rd life' How do I construct the trade space
Underpinning science to create 'Design for sustainability tools' How do I construct the tradespace?
Modifying materials for application -Design requirement driven
Need to be able to demonstrate reuse of degraded polymers-what pre-processing needs done to turn that into feedstock?
Low cost reconfigurable & recyclable tooling
Vitrimers & Recyclamine type polymers
Exotherm /quality control of bio-based resins
Design tool for mixed fibre structures CF & GF & NFs
Design tools for mixtures of variable length and degrees of orientation. How to get to a point to convince a regulator
Automated remake processes for life +1
Thermoplastic composite recycling
Investigate wetting of recycled fibres - how do luck of sizing effect wetting & resulting composite properties
New tools for coupling b/w manufacturing and structural assessment for discrete forms
Mechanical testing and modelling of precursors for sustainable materials
Depolymerisation
Characterisation of out-of-plane properties of discontinuous fibre materials
Parametric study to grade recycled material
Optimisation of comp design: -hybrid fibres -ply angles (double-double) -rcf clamping

Data Reduction - Categorising identified challenges into sub-themes and their frequency

Sub-theme	Frequency
Lack of material data, including lifecycle analysis data and environmental impact data	71
Lack of and validity of process data	42
Lack of composites standards and ways to analyse recycled fibre properties	37
Lack of lifecycle analysis education	27
Need for economic analysis of processes	35
Challenges with the implementation of automated manufacture	23
Low/non-existent market acceptance of recycled components	16
Low mechanical and physical properties of recyclates	12
Recycled fibres are not suitable for virgin processes	25
Fragmented supply chain	13
No incorporation of waste management into the manufacturing design stage	8
Poor integration of all process steps leading to bottlenecks	15
High costs involved in recycling processes	12
Non-optimal pattern cutting and mould tooling	15
Need for better separation of multi-component materials for recycling	4
High energy costs for large structure manufacture	13
Need more effective ways to analyse recycled fibre properties	17
Need for increased use of additives/alternative materials to increase recovery efficiency	26
Lack and validity of available software for design and process simulation	11
Need for more natural fibres/resins in the manufacturing supply chain	18
Dismantling and demanufacturing of large structures	8
Need applications for recycled resins	11
Complexity in recycling methods, e.g., thermoplastics	20
Need for novel fibre alignment methods	13
Skill gaps in process equipment and design software	7

Recycling infrastructure not suitable for large structures	8
Need for reversible joining techniques	5
Need for out-of-autoclave processes and reduced energy use in curing	22
Reuse or negation of tooling	8
Need for further optimisation of resins	12
Need for scalability in recycling processes	6
Lack of remedial repair methods	10
The low value of waste materials	9
Challenge of recycling glass fibres	8
Need for more effective knowledge transfer from other sectors	
High cost of consumables	7
Need for better translation of industry need to academic research	5
Optimise or remove the need for freezer storage of prepreg	7
Lack of competition in the UK recycling market leading to poor market traction	4
Risks involved in recycling processes (solvolysis/pyrolysis) need to reduce for wider adoption	3
Significant time and space requirements needed for waste collection	2
Need for upcycling of end-of-life components where recycling is not applicable	

Sustainability Workshop III – Held at the AMRC

The third workshop held at the AMRC in October 2022 (Sustainability Workshop III) saw different attendees to that of the NCC workshop to ensure all views and comments were captured, reflecting the largest representation of the Hub and industrial partners. In total 274 challenges were identified within Sustainability Workshop II and III.

Challenges were identified based on four key themes – recycling methodologies, lifecycle assessment, sustainability in composite manufacturing processes and composite design and manufacturing with sustainable materials. These challenges were then further categorised into a series of sub-themes.

Raw Data - Composites Recycling Methodologies

Challenge
challenging to transfer knowledge across the supply chain
building confidence in properties of recycled composites
categorising composites for bulk recycling
recycling of stripped polymers after products such as decom
how to bring in other disciplines and KT from other sectors (e.g. plastics and packaging)
how to maintain quality and confidence in recyclate
challenge how to sort and extract material before it is shredded
how to measure quality and ID matrix products that are recycled
meaningful measurable recyclate
difficult to control parameters in pyrolysis i.e. char
difficult to scale up fluidised bed, still lab scale
design for recycling - how to deal with ill-informed policy e.g. energy recovery
complex to sort composites post-shredding
fibre characterisation after recycling
legislation will drive recycling
new chemistry of matrix (vitrimers methocrylate)
biofibres' end of life is methane'
co2 emissions for recycling must be lower than virgin
quality of recycled fibre
economic viability (cost of recycled vs virgin fibre)
manufacturers will pay for end of life
recycling of glass fibres - possible? feasible?
trust in data
material identification standard (blockchain/historic record)
extend life by rework, revalidation (continuous Structural Health Monitoring? Prediction of maintenance)
a Hub topic - develop processes to take recycled material, separation technology is important
no market. Quality, certification, costs and markets. Not a research challenge, legislation will follow technology
keep as much embodied energy/properties in play as long as possible
verification via public database, specify trusted data, open standard
glass: cant recycle, RTO in glass, glass futures, st Helens
the need to extend life, to limit extent of manufacturing waste, recertification, NDT/inspection
flax production actually produces more co2 to take fibre out of glass
new chemistry e.g. vitrimers

Raw Data - Composites LCA Processes

Challenge
capture of energy used in manufacturing
greenwashing
food data as example content on label - calories, fat, sugar etc
trusted LCA data (should this be on data sheets)
public funded assessment body, FIA, Euro NCAP

traffic light system like food packaging
could record data from what is produced in Hub. Create our own data, LCA education
is an international standard for LCA but provenance is important done once or twice
aggregation data in LCA databases, grade data 1-6
public want to do the right thing but need right info, source of truth not marketing
consistency of LCA?
look at what other institutions are doing on LCA, not just in composites
LCA means different things to different people
challenge in storing material data - codification/HDF5?
primary data measurement for LCA?
LCA processes not an engineering standard but taught more to undergraduate - should it be a standard?
do we need a global governing body for LCA? E.g. FDA/British/European
how to embed LCA into design and expand for reporting into decision making optimisation of process
predictive LCA (AI?) to populate data gaps or develop new processes
how to make LCA cost affordable
how to embed LCA into academic courses
how to get simple LCA metrics for consumers

Raw Data - Sustainability in Composite Manufacturing Processes

Challenge
feasibility question - what is digital twin, why for composites
how to reduce consumable wastage
how to lower energy costs
in process waste packaging etc
ambiguous descriptions of what a true digital twin actually is
how to increase acceptability of reusable consumables
reconfigurable tooling
can you make carbon-carbon brake discs from old PMCs?
need to move away from prepreg - guarantees quality right first time
certification is a barrier
wing of tomorrow is dry fibre
making things with zero waste
scrap material costs are huge
heat recovery needs processes 90D out of phase
tooling a huge challenge and other things in making tool not cost too much
WT blades, 1% of cost of aircraft blades mostly tension loading with bit of bending
invar: hugely expensive, difficult to machine, lots of waste. Use in-process waste for tooling
cure kinetics is a consideration and getting rid of nasties

Raw Data - Composites Design and Manufacturing with Sustainable Materials

Challenge
more use of recycled carbon fibre in CFRP tooling
overmoulding recycled material reinforcement structures over virgin materials
how to separate mixed composite
how to design for sustainability without known EOL routes
discontinuous fibre disassembly further research on disbondable adhesives
design for disassembly, some work at UoSL on UV. But not got to expose to unzipping force/action during life
making things from recycled material e.g. hiperdif
language is important, recycled = poor quality
should we be lobbying more?
next Hub - got to have a thermoplastic focus. Epoxy 5EUR/kg, PEEK 40EUR/kg, vitrimer >50EUR/kg

Data Reduction - Categorising identified challenges into sub-themes and their frequency

Sub-theme	Frequency
Lack of material data, including lifecycle analysis data and environmental impact data	41
Lack of and validity of process data	24
Lack of composites standards and ways to analyse recycled fibre properties	49
Lack of lifecycle analysis education	30
Need for economic analysis of processes	17
Challenges with the implementation of automated manufacture	16
Low/non-existent market acceptance of recycled components	10
Low mechanical and physical properties of recyclates	7
Recycled fibres are not suitable for virgin processes	9
Fragmented supply chain	11
No incorporation of waste management into the manufacturing design stage	7
Poor integration of all process steps leading to bottlenecks	13
High costs involved in recycling processes	3
Non-optimal pattern cutting and mould tooling	7
Need for better separation of multi-component materials for recycling	7
High energy costs for large structure manufacture	4
Need more effective ways to analyse recycled fibre properties	7
Need for increased use of additives/alternative materials to increase recovery efficiency	15
Lack and validity of available software for design and process simulation	8
Need for more natural fibres/resins in the manufacturing supply chain	6
Dismantling and demanufacturing of large structures	1
Need applications for recycled resins	3
Complexity in recycling methods, e.g., thermoplastics	1
Need for novel fibre alignment methods	

Skill gaps in process equipment and design software	8
Recycling infrastructure not suitable for large structures	1
Need for reversible joining techniques	3
Need for out-of-autoclave processes and reduced energy use in curing	12
Reuse or negation of tooling	7
Need for further optimisation of resins	3
Need for scalability in recycling processes	2
Lack of remedial repair methods	3
The low value of waste materials	1
Challenge of recycling glass fibres	4
Need for more effective knowledge transfer from other sectors	11
High cost of consumables	3
Need for better translation of industry need to academic research	3
Optimise or remove the need for freezer storage of prepreg	1
Lack of competition in the UK recycling market leading to poor market traction	1
Risks involved in recycling processes (solvolysis/pyrolysis) need to reduce for wider adoption	1
Significant time and space requirements needed for waste collection	
Need for upcycling of end-of-life components where recycling is not applicable	3

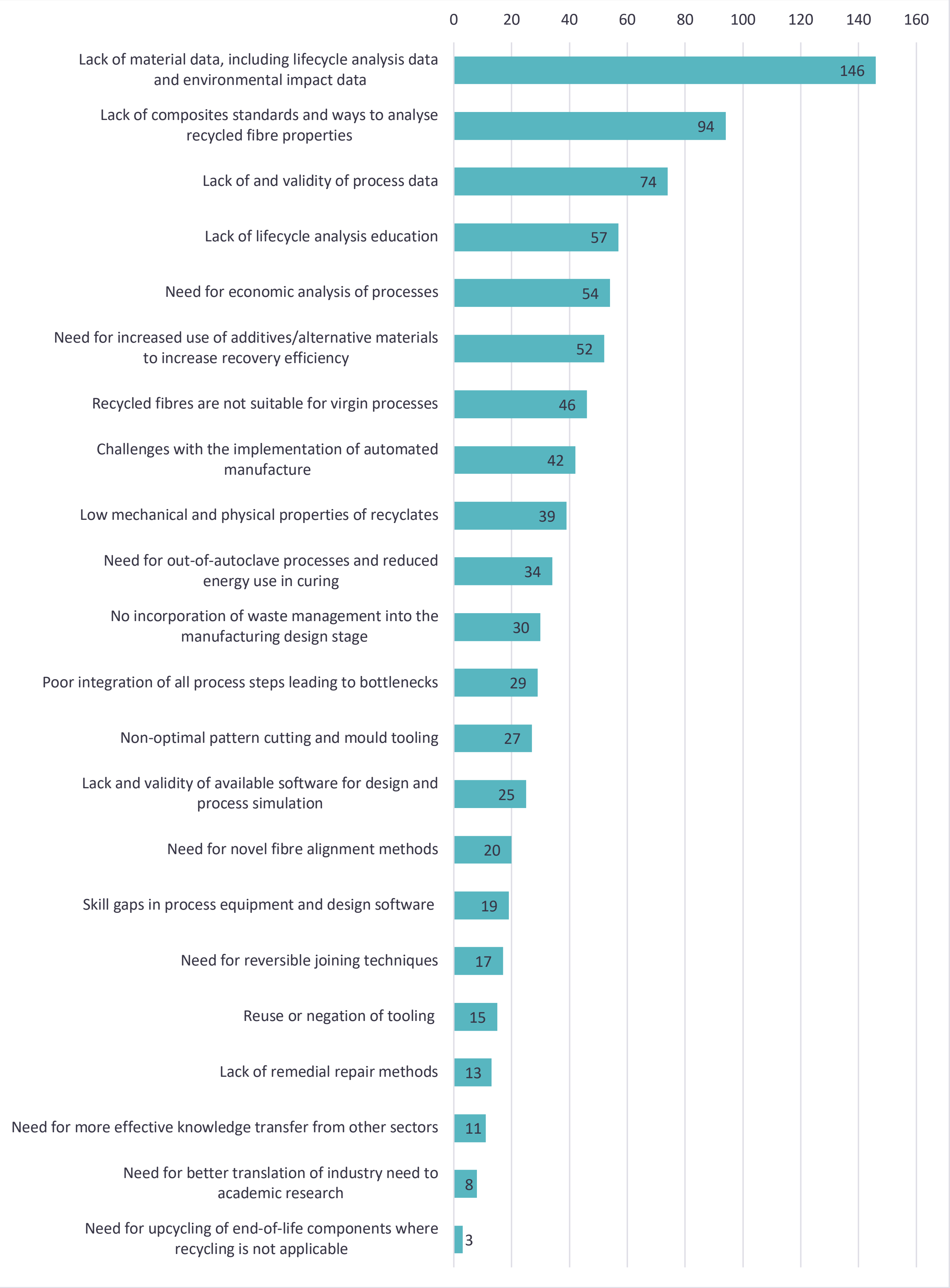
Comparison of sub-theme data and challenge data for all workshops

Sub-theme	Workshop I	Workshop II	Workshop III	Total
Lack of material data, including lifecycle analysis data and environmental impact data	34	71	41	**146**
Lack of and validity of process data	8	42	24	**74**
Lack of composites standards and ways to analyse recycled fibre properties	8	37	49	**94**
Lack of lifecycle analysis education		27	30	**57**
Need for economic analysis of processes	2	35	17	**54**
Challenges with the implementation of automated manufacture	3	23	16	**42**
Low/non-existent market acceptance of recycled components	12	16	10	**38**
Low mechanical and physical properties of recyclates	20	12	7	**39**
Recycled fibres are not suitable for virgin processes	12	25	9	**46**
Fragmented supply chain	8	13	11	**32**
No incorporation of waste management into the manufacturing design stage	15	8	7	**30**
Poor integration of all process steps leading to bottlenecks	1	15	13	**29**
High costs involved in recycling processes	13	12	3	**28**
Non-optimal pattern cutting and mould tooling	5	15	7	**27**
Need for better separation of multi-component materials for recycling	16	4	7	**27**
High energy costs for large structure manufacture	10	13	4	**27**
Need more effective ways to analyse recycled fibre properties	2	17	7	**26**
Need for increased use of additives/alternative materials to increase recovery efficiency	11	26	15	**52**
Lack and validity of available software for design and process simulation	6	11	8	**25**
Need for more natural fibres/resins in the manufacturing supply chain		18	6	**24**
Dismantling and demanufacturing of large structures	15	8	1	**24**
Need applications for recycled resins	7	11	3	**21**
Complexity in recycling methods, e.g., thermoplastics		20	1	**21**
Need for novel fibre alignment methods	7	13		**20**
Skill gaps in process equipment and design software	4	7	8	**19**
Recycling infrastructure not suitable for large structures	10	8	1	**19**
Need for reversible joining techniques	9	5	3	**17**
Need for out-of-autoclave processes and reduced energy use in curing		22	12	**34**
Reuse or negation of tooling		8	7	**15**
Need for further optimisation of resins		12	3	**15**
Need for scalability in recycling processes	7	6	2	**15**
Lack of remedial repair methods		10	3	**13**
The low value of waste materials	3	9	1	**13**
Challenge of recycling glass fibres		8	4	**12**
Need for more effective knowledge transfer from other sectors			11	**11**
High cost of consumables		7	3	**10**
Need for better translation of industry need to academic research		5	3	**8**
Optimise or remove the need for freezer storage of prepreg		7	1	**8**
Lack of competition in the UK recycling market leading to poor market traction	1	4	1	**6**
Risks involved in recycling processes (solvolysis/pyrolysis) need to reduce for wider adoption	2	3	1	**6**
Significant time and space requirements needed for waste collection	4	2		**6**
Need for upcycling of end-of-life components where recycling is not applicable			3	**3**
Total	565	679	351	**1207**

The sub-themes were then labelled as being within the scope of the Hub. Those within scope are then further discussed below to determine the potential for specific research projects that align with industry needs and challenges, all underpinned by the necessity of sustainability within composites manufacturing.

Sub-theme	Total	In Scope	Possibly within Scope	Not in Scope
Lack of material data, including lifecycle analysis data and environmental impact data	146	🟩		
Lack of and validity of process data	74	🟩		
Lack of composites standards and ways to analyse recycled fibre properties	94	🟩		
Lack of lifecycle analysis education	57	🟩		
Need for economic analysis of processes	54	🟩		
Challenges with the implementation of automated manufacture	42	🟩		
Low/non-existent market acceptance of recycled components	38			🟥
Low mechanical and physical properties of recyclates	39	🟩		
Recycled fibres are not suitable for virgin processes	46	🟩		
Fragmented supply chain	32			🟥
No incorporation of waste management into the manufacturing design stage	30		🟧	
Poor integration of all process steps leading to bottlenecks	29	🟩		
High costs involved in recycling processes	28			🟥
Non-optimal pattern cutting and mould tooling	27	🟩		
Need for better separation of multi-component materials for recycling	27			🟥
High energy costs for large structure manufacture	27			🟥
Need for increased use of additives/alternative materials to increase recovery efficiency	52	🟩		
Lack and validity of available software for design and process simulation	25	🟩		
Need for more natural fibres/resins in the manufacturing supply chain	24			🟥
Dismantling and demanufacturing of large structures	24			🟥
Need applications for recycled resins	21			🟥
Complexity in recycling methods, e.g., thermoplastics	21			🟥
Need for novel fibre alignment methods	20	🟩		
Skill gaps in process equipment and design software	19	🟩		
Recycling infrastructure not suitable for large structures	19			🟥
Need for reversible joining techniques	17		🟧	
Need for out-of-autoclave processes and reduced energy use in curing	34	🟩		
Reuse or negation of tooling	15		🟧	
Need for further optimisation of resins	15			🟥
Need for scalability in recycling processes	15			🟥
Lack of remedial repair methods	13	🟩		
The low value of waste materials	13			🟥
Challenge of recycling glass fibres	12			🟥
Need for more effective knowledge transfer from other sectors	11	🟩		
High cost of consumables	10			🟥
Need for better translation of industry need to academic research	8	🟩		
Optimise or remove the need for freezer storage of prepreg	8			🟥
Lack of competition in the UK recycling market leading to poor market traction	6			🟥
Risks involved in recycling processes (solvolysis/pyrolysis) need to reduce for wider adoption	6			🟥
Significant time and space requirements needed for waste collection	6			🟥
Need for upcycling of end-of-life components where recycling is not applicable	3	🟩		
Total	**1207**	**25**	**3**	**19**

Twenty-two sub-themes were derived from the challenges identified in the three sustainability workshops, with twenty within scope and three possibly within scope.

0
20
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Lack of material data, including lifecycle analysis data and environmental impact data
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Lack of composites standards and ways to analyse recycled fibre properties
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Lack of remedial repair methods
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Need for more effective knowledge transfer from other sectors
11
Need for better translation of industry need to academic research
8
Need for upcycling of end-of-life components where recycling is not applicable
3

Discussion of in-scope sub-themes:

It is important to state a few observations of the data before going into detail regarding the individual challenges presented and the potential research themes these could give rise to.

1. Due to the nature of the sustainability workshop subgroup themes (e.g., LCA) there are overlaps in the data and sub-themes produced.
2. Many of the sub-themes generated from the comments are design related, or specifically relate to the pre-manufacturing of composite components.
3. Many of the sub-themes are common to all composite manufacturing.

This discussion aims to address identified patterns within the 460 industry-identified challenges collated from the three Hub sustainability workshop activities and expand on the 22 sub-themes that encapsulate these challenges while ensuring that the discussion of potential research is within a sustainability context where possible. It is worth noting that not all sub-themes or challenges have a specific sustainability element, such as those relating to technical skill gaps, and in these situations, examples have been used with a loose association – e.g., technical skills gaps could refer to those related to design software therefore non-optimal component design leading to higher material wastage.

It is also important to note that some of the industry-led challenges do not necessarily involve fundamental engineering to provide a solution, such as those relating to the lack of competition in the composites market or those challenges relating to the lack of economic analysis of current processes.

Regarding the ‘Net-Zero Ambitions’ described in the report’s Introduction, several of the identified sub-themes apply to more than just one of these ambitions and that multidisciplinarity could serve a significant role in the solutions to the challenges these represent. For example, where *‘lack of available and validated software for design and simulation’* appears under *Zero Inspection* and *Zero Prototyping*, the variation in the applicable software warrants the input of not just composite engineering expertise but also computer science engineers and mathematicians.
The sub-themes have been labelled as being within the scope of the Hub’s research agenda or otherwise, and those that have been deemed within or partially within scope are presented below.

1. *Lack of material data, including lifecycle analysis data and environmental impact data.*

There needs to be more data relating to materials, e.g., more information provided by manufacturers on data sheets to suitably describe a product in terms of its lifecycle (energy used to create the product in the factory or amount of CO2 produced in the manufacturing process). This information is critical to understanding embodied energy within composites and justifying their use at the design stage.

2. *Lack of and validity of process data.*

This relates to the need for more data from individual processes within composite manufacturing, such as specific information surrounding fibre alignment in recycled composite parts. This leads to the inability to understand the final material strength or other characteristics without subjecting it to metrology testing.

3. *Lack of composites standards and ways to analyse recycled fibre properties.*

There is a clear overlap with point 1 above; however, expanding on this there need to be more official standards within the composite community. Adopting standardisation would help reduce the complexity of composite adaptability and help make the adoption of composite materials quicker and easier.

Owing to the nature of recycled (discontinuous) fibres, the material properties of a recycled component can vary greatly either between recycled and virgin materials or between those recycled materials within a single component. Therefore, it is vital that for the market to accept parts made from recycled composite materials readily, we understand their structural capabilities and can easily predict the properties of a recycled part before their manufacture. This ties in with the need for official composite standards and stricter/more complete material data collection.

4. *Lack of lifecycle analysis education.*

Lifecycle analysis principles are often taught at the undergraduate level at universities, but there is a strong argument for making this a compulsory element in engineering education. It is also essential that LCA is discussed, taught, and continuously improved upon within the composite manufacturing industry, supported by academic institutions and governmental standardisation.

5. *Need for economic analysis of processes.*

Though considerable documentation is available on materials and individual manufacturing processes, more is still required to paint a better picture of the efficacy, efficiency, and optimality of composite manufacturing at all TRL stages in an economic context. By improving the technical analysis of processes, more control over them can be achieved and thus resulting in potentially superior products with less wastage – both in time, material, energy, and cost.

6. *Challenges with the implementation of automated manufacture.*

Significant reductions in time and costs could be achieved by introducing automation to historically manual processes. Increased automation within the manufacturing loop would also lead to high repeat part quality, independent of production location or skilled labour, and high cost-efficiency and in turn reduced environmental impact of the manufacturing process.

7. *Low mechanical and physical properties of recovered fibres.*

a) Thermal-mechanical and thermo-oxidative degradations and fibre breakage lead to the poor mechanical performance of composite recyclates, and therefore poor overall component quality. More research needs to be undertaken to develop novel recyclable composites where the translation of recycled fibre properties to overall component performance is more readily understood.
b) Physical properties are affected by contaminants, such as residual char, and limit the use of high-performance processes, thereby affecting the overall quality of the recycled component.

8. *Recycled fibres are not suitable for virgin processes.*

Though there are barriers to the large-scale uptake of composites into the broader marketplace, manufacturing products from recycled composites remains a particularly significant hurdle. Due to the nature of recycled composites, i.e., discontinuous fibres, the same manufacturing processes used for virgin carbon fibre cannot be used, such as filament winding, braiding, or textile conversion processes owing to the need for continuous fibre lengths. There are no guarantees that the fibre in recycled form can perform at the levels required for specific applications – this relates to the need for material traceability and official standards, tying in with point 3. Ultimately this comes down to whether we develop new processes or do we develop intermediates that fit into current ones.

9. *No incorporation of waste management into the manufacturing design stage.*

Many comments referred to the challenges surrounding the need for planning ahead of manufacture and that all recycling processes must have the ability to handle all potential composite waste types economically. A lot of these comments relate to design for manufacture/early stage design knowledge, and hence there are overlaps with other sub-themes. However, it is important to distinguish that waste management is a key aspect of the design process and identifying the pathways to reuse e.g., selvedge testing is a clear challenge within the design for manufacture theme in its own right.

10. *Poor integration of all process steps leading to bottlenecks.*

The alignment of all steps in the composite manufacturing process allows for greater control and quality of the product. When it comes to recycling the profit, margins are likely to be low, and therefore there will be a significant drive to better align the vertical integration elements in order to maximise profits. However, previous attempts to create vertically integrated supply chains in composite manufacture (one person creates the fibre, another weaves it, another prepregs it etc.), have failed. Thus the challenge in vertical alignment is significant and must be overcome if the recycling of composites were to become economically viable.

11. *Non-optimal pattern cutting and mould tooling.*

Automation of cutting equipment can reduce production times and costs relating to labour. Cutting software can further optimise this process and minimise material wastage (such as nesting algorithms), significantly impacting the cost when using prepreg. Optimisation of mould tooling can not only reduce unnecessary wastage but can improve curing efficiency and uniformity. By implementing modular tooling, it is feasible that once a tool has reached the end of its specific application lifespan, that it can be dismantled and reformed for another mould, thereby becoming an element of the composite circular economy.

12. *Need for increased use of additives/alternative materials to increase recovery efficiency.*

At the end-of-life stage of a component adding chemical agents to fibre matrices to increase the quality of the recovered fibres has been shown to be effective at the end-of-life stage of the composite component. For example, a recyclable thermosetting resin can be used with the virgin fibres and then degraded into constituent carbon/glass fibres and oligomers ready to be remanufactured, thereby resulting in a closed loop manufacturing process.

Optimising recycling/degradation processes is critical to circularity in composite manufacturing. Where process outputs are deemed either hazardous or worthless (solvolysis creating a toxic slurry and pyrolysis resulting in unusable char), the fact remains that the processes themselves are generally inefficient e.g., remains of residual chart post-pyrolysis. More research is required to ascertain whether adding new materials to the matrix would result in a higher output of useful material or lower/altogether remove the health and safety risks of the recycling process.

13. *Lack and validity of available software for design and process simulation.*

Through the appropriate usage of machine learning and artificial intelligence, optimisations in manufacturing processes can also be achieved, leading to pre-manufacture defect detection potentially through digital twins, on-the-fly parameter corrections and real-time process data. Through the effective use of software, the conversion of fundamental research into mature, usable and commercially available research can be accelerated.

14. *Need for novel fibre alignment methods.*

It is widely known that optimal fibre alignment within a composite matrix will determine the overall performance in mechanical strength, whereby fibre alignment parallel to the direction of loading will yield the best strength and stiffness. Where several technologies, be that hardware or software, have been developed to ascertain these optimal alignments, further research is required to ensure that every loading scenario can be effectively simulated, again reducing the potential for material wastage due to non-adherence to the stringent tolerances required by specific industries such as aerospace.

15. *Skill gaps in process equipment and design software.*

One of the principal challenges to realising the advantages of composite materials is a widely accepted skills shortage, be that in recruitment across industry and academia and its inability to keep pace with the market demand. Special skills shortages are those in composite design through CAD, programming, and modelling. Given the importance of sustainability in manufacturing to align with worldwide Net Zero goals, the need for software capable of reducing energy, wastage, costs and time is being invested more than ever. However, engineers require the skills to operate these innovations in software and hardware. Therefore, focusing on education within industry and academia is critical to ensuring that technology moves forward and benefits as many people as possible.

16. Need for reversible joining techniques.

The case for reversible composite bonding is strong; where quick-forming thermoset plastic adhesives have successfully bonded multiple materials, there is no way to reverse the join for repair or part replacement. Advances in thermoplastic adhesives have enabled methods for non-destructive disbonding of composite components. However, more research is required to reduce the cost of reversible joint adhesives and make their use more widespread within the industry.

17. Need for out-of-autoclave processes and reduced energy use in curing.

Out-of-autoclave (OOA) processes need to achieve comparative quality as in-autoclave curing by eliminating voids and achieving desired fibre content by applying pressure, vacuum and heat by an alternative means. Resin Transfer Moulding (RTM) remains a standard method of OOA manufacturing but is subject to challenges relating to parameter controls such as uniformity of resin infusion and flow rate. High microporosity levels also remain an issue, and the 2% tolerance levels required by the aerospace industry continue to present a challenge in composites research.

The curing of composites has mostly stayed the same since they were first introduced and still relies upon ovens and autoclaves. Given the necessity of lowering energy costs in the current climate, novel curing methods are very much in the interest of small-scale manufacturers and multinationals. Though many developments have been made, such as those including microwave curing and radio frequency heating, the ability to control exothermic reactions effectively and uniform heating, all while consuming low levels of power, remains a significant challenge. Therefore, further research in alternative curing methods is a key target in the future of composite manufacturing and wider industry adoption.

18. Reuse or negation of tooling.

Tooling carries considerable costs that are typically amortised over the number of parts manufactured using that single mould. Though it can sometimes be challenging to estimate the number of parts that can be made due to fluctuating demand or potential manufacturing errors (e.g., damaging the mould during pressing) requiring mid-process mould replacement, the costs can spiral significantly with little warning. Therefore, more research must be conducted on alternative tooling materials and extending tool life expectancy.

19. Lack of remedial repair methods.

If damage occurs, then it is likely that a composite component will have reduced functionality, and the choice will be to replace or repair. Where replacement parts can potentially be costly, repair offers a cost and time-effective solution in many circumstances. However, repairing a composite part is not necessarily straightforward and depends on the details of the structure and is usually on a case-by-case basis and can be either in the form of filling, injection, fastening or bonding; each presenting its own challenges. Ultimately, there is a need for a lifecycle based approach to assess the best path, factoring in the lowest environmental impact of the chosen path.

20. Need for more effective knowledge transfer from other sectors.

Knowledge transfer has already been identified as a pivotal element of innovation, accelerating competitive advantages in all markets, industries, and academic institutions. It has been shown that transferring information from one project to another supports workers by using existing, tested knowledge to address their challenges rather than repeating the same errors. Therefore, an organisation such as the Hub must ensure that a streamlined knowledge exchange process is in place to publicise best practices and optimise all aspects of composites research.

21. *Need for better translation of industry need to academic research.*

The need for knowledge translation, in this case from industry to academia, is significant. Fundamental research, as is the practice of the Hub is principally guided by the sector's needs and ultimately begins the TRL journey of a research project from a feasibility study to a core project to a technology pull-through to industry application. Therefore, it is pivotal that the initial industry need is translated effectively and accurately into a research aim that can form the basis of the TRL roadmap. Key to this is communication, market trend awareness and technology landscape analysis.

22. *Need for upcycling of end-of-life components where recycling is not applicable.*

With current studies indicating that waste carbon fibre-reinforced plastic (CFRP) from end-of-life commercial aircraft and wind turbine blades expecting to reach 500,000 tons and 483,000 tons respectively, by 2050, there is an urgent need to recycle or, better still, upcycle effectively. Recycling methods, including pyrolysis, solvolysis, and mechanical approaches, each have challenges. Still, there is yet to be a current CFRP recycling method that can improve carbon fibres' performance. Any novel way for upcycling CFRP would attract widespread attention, and it is a key driver in composite adoption.