Institution: University of Warwick
Unit of Assessment: B12 – Engineering
Title of case study: Recycling Waste Carbon Fibre: bringing new products to market, creating jobs in the local economy and meeting environmental standards
Period when the underpinning research was undertaken: 2008-2017
Details of staff conducting the underpinning research from the submitting unit:

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Kerry Kirwan	Professor	2002 – Present
Stuart Coles	Associate Professor	2006 – Present
James Meredith	Project Manager	2008 – 2013; 2018 – Present

Period when the claimed impact occurred: 2014-2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

Building on materials processing and characterisation expertise within Professor Kerry Kirwan's team, research at the University of Warwick sought to establish the technical and commercial viability of recycled carbon fibre reinforced polymer (CFRP) in high-performance manufacturing industries, including automotive and aerospace. A collaboration with local employer and industrial partner ELG Carbon Fibre Ltd. led to development of the innovative lightweight Carbiso range of materials, achieving GBP2,000,000 sales annually and now in use by companies across 26 countries, including [text removed for publication]. Through Warwick enabling mass production this has driven the innate environmental benefits of using recycled materials: ELG Carbon Fibre's 1,700t capacity plant has a concomitant saving of 52,700tCO_2e/year in global warming potential vs. virgin carbon fibre production.

2. Underpinning research (indicative maximum 500 words)

Carbon fibre reinforced polymer (CFRP) is a highly valuable engineering material that offers greater strength, stiffness and energy absorption at a one-quarter of the density of steel. To make CFRP composites, layers of long fibre mats pre-impregnated with a thermosetting or thermoplastic polymer matrix (prepreg) are compressed at elevated temperature, or short fibres and liquid polymer injected/extruded into a mould/die, to produce a strong, lightweight fibre-polymer composite. Whilst the use of CFRP provides more sustainable transportation solutions and reduced carbon emissions through vehicle and aircraft light-weighting, its production and end-of-life disposal have a far greater environmental impact than any metal; with up to 40% of CFRP going to landfill.

From 2006, Professor Kerry Kirwan of the Warwick Manufacturing Group department (WMG) began to explore high-value feedstocks (raw materials to supply or fuel industrial processes) from natural sources and waste streams. One waste material for a zero waste to landfill solution was carbon fibre from CFRP manufacturing. In 2008 a working relationship started when early experimental materials from ELG Carbon Fibre (ELGCF) Ltd, one of the largest carbon fibre recycling plants in the world, were introduced into the University's WorldF3rst racing car **[G1]**. Formal collaboration with ELGCF began in earnest in 2014, seeking to establish both technical and commercial viability of using recycled carbon fibre (rCF) in industrial applications. Research outputs by Professor Kerry Kirwan, Dr Stuart Coles, Dr James Meredith and Dr Peter Wilson at Warwick continue to drive circular economic innovation to this day.

The WorldF3rst Formula 3 racing car hit the headlines in 2009 for its creative use of biocomposites. Less well publicised, but of technological importance, was the incorporation of rCF composites into the vehicle's rear wing. Though the recycled carbon fibres in this example were used principally for light-weighting, and not to provide a safety-critical structure, the fact alone that the material had been used in a vehicle seeded the idea of using the rCF in higher performance applications, stimulating further research:

Comparison of properties for different types of carbon fibre: From 2010 to 2012, Meredith, Coles and Kirwan compared the mechanical properties of *recycled*, *fresh* (virgin) and *aged* (out-of-life) carbon fibre prepreg **[3.1].** To accomplish this, the compressive, tensile and flexural strength plus modulus of their resulting composite laminates were tested to ASTM and CRAG standards. Additionally, and in contrast to established conventional static impact tests, a novel methodology for dynamic impact tower testing was developed. Using a conical composite geometry to more accurately replicate motorsport structures, the dynamic test method was representative of the forces observed in higher performance applications (e.g. in vehicle collisions) **[3.1]**. An epoxy-based resin matrix was employed throughout, with matrix choice serving only to provide a consistent baseline for evaluating the energy absorption of the different fibre types.

The energy absorption properties for the rCF composite, assessed from compressive strength test results, gave around 95% performance of the comparable virgin fibre composites at only a fraction of the embodied energy required in the laminate production **[3.1]**. Not only did this outcome provide ELGCF with a strong justification for use of rCFs in higher performance applications which they could use to attract new clients, but it also offered a rigorous understanding of rCF which would underpin later development of know-how by WMG. This supported the optimization of processes for ELGCF's chopped rCF range, namely the Carbiso C, CT and CT+ products.

Weighing cost against quality: In order to establish the commercial potential for a cheaper feedstock and production methods, any cost savings must be weighed-up against reductions in product quality (for example, the 5% performance loss characterised for rCF **[3.1]**). Between 2012 and 2014 the WMG team measured the energy absorption capacity of conical samples made with different layups and through different methods of curing. The results were normalised by the cost of manufacture (materials and process) to give the specific energy absorption, with the fibre volume fraction as well as voidage also characterised. Results demonstrated that robust performance can still be met with lower cost materials and processes **[3.2]**.

Transfer of knowledge from **[3.2]** was readily made into ELGCF's own rCF product development, integrating into their own design-cost analysis and providing a means to illustrate value for money to potential clients. Additionally, through quantifying the void volume fraction, a key insight into how varying curing conditions could achieve superior wet-out of fibres was gained. This research was directly adapted for characterising other laminate matrices, resulting in the subsequent shorter production cycle duration (while maintaining product integrity and eliminating voids) in ELGCF's thermoplastic prepreg range (Carbiso TM).

Product development – advancing through technology readiness levels (TRLs): In 2015 WMG and ELGCF were jointly awarded a research grant from the Advanced Manufacturing Supply Chain Initiative (AMSCI) by Finance Birmingham **[G2]**, specifically to develop ELGCF's rCF thermoplastic products for automotive applications. AMSCI's aim was to enhance supply chains in the UK, with rCFs promising an alternative method to supply the world's colossal carbon fibre demand (estimated at 98,000t in 2020) and thereby improve supply chain security. This grant funding provided the seed for key production impacts, building on existing knowledge **[3.1-3.2]**, particularly for ELGCF's own thermoplastic prepreg range (Carbiso TM), successfully advancing product development through TRLs by improving the capacity for bulk production.

Alongside the AMSCI award, several other product development avenues were explored between 2015 and 2019 by Kirwan and Coles **[3.3]**. This research determined tensile strengths of CFRPs containing different percentages of milled rCF, and using different percentages of epoxidised vegetable oil in the matrix (fresh, waste or purified from waste). The main insights gained were that using 30% weight rCF gave greater tensile strength than virgin carbon fibre alone, and that there was a negligible difference in tensile strength when using epoxy resin made from 10% per weight purified vegetable oil from waste sources. Additionally, research by Coles explored the modification of the fibre-matrix interface of natural fibres, utilising different fibre coatings **[3.4]**, analogous to the work carried out on the Carbiso TM range. These papers **[3.3-3.4]** demonstrate the use of different strategies to solve the persistent problem of improving the fibre-matrix interface, and furthered knowledge of which additives are well suited to composite structures.

Insights from these findings **[3.3-3.4]** led to analogous new developments in modifying both the polymer matrix and the surface of rCFs in ELGCF's products, which remains an active area of collaboration. In particular, maleic anhydride-grafted polypropylene incorporation into the matrix and the electrochemical alteration of the fibres themselves were both successfully investigated. While the specific methodologies and processes which have catapulted ELGCF to sector-leading success must remain a commercial secret, the principles which equipped WMG with know-how to enhance the company's production are all captured in the published research **[3.1-3.4]**.

3. References to the research (indicative maximum of six references) **Warwick = Bold**

All research papers were published in peer-reviewed journals

[3.1] Meredith, J., Cozien-Cazuc, S., Collings, E., Carter, S., Alsop, S., Lever, J., **Coles, S. R.,** Wood, B. M. and **Kirwan, K.** *Recycled carbon fibre for high performance energy absorption* (2012), Composites Science and Technology, 72 (6). pp. 688-695. doi:10.1016/j.compscitech.2012.01.017

[3.2] Meredith, J., **Bilson, E.**, **Powe, R.**, **Collings, E.** and **Kirwan, K.** (2015) *A performance versus cost analysis of prepreg carbon fibre epoxy energy absorption structures*. Composite Structures, 124. pp. 206-213. doi:10.1016/j.compstruct.2015.01.022

[3.3] Fernandes, F. C., **Kirwan, K.**, **Lehane, D.** and **Coles, S. R.** (2017) *Epoxy resin blends and composites from waste vegetable oil*. European Polymer Journal, 89. pp. 449-460. doi:10.1016/j.eurpolymj.2017.02.005

[3.4] Fernandes, F. C., **Kirwan, K.**, **Wilson, P. R.** and **Coles, S. R.** (2019) *Sustainable Alternative Composites Using Waste Vegetable Oil Based Resins. Journal of Polymers and the Environment*, 27 (11). pp. 2464-2477. doi:10.1007/s10924-019-01534-8

Key Grants:

[G1] Young, K. (PI), **Dashwood, R. J. (PI)**, **Kirwan, K.** and **30 additional Co-Investigators**, *Warwick Innovative Manufacturing Research Centre Phase II*. **Sponsor:** EPSRC [EP/G049971/1] **Duration:** Apr 2008 - Dec 2011 **Award:** GBP6,880,763

[G2] Kirwan, K. (PI), **Coles, S.** and **McNally, T.**, *Advanced Manufacturing Supply Chain Initiative (AMSCI): Recycled Carbon Fibre for Automotive Thermoplastics - RECAT*. **Sponsor:** Finance Birmingham (through Birmingham City Council) [WMLCR019 - RP 1699]. **Duration:** Nov 2015 – Dec 2016 **Award:** GBP199,882

Leveraged over **GBP100,000 direct contract research funding from ELG Carbon Fibre,** with match funding from the WMG Centre High Value Manufacturing (HVM) Catapult.

4. Details of the impact (indicative maximum 750 words)

A mutually beneficial industrial collaboration with ELG Carbon Fibre (ELGCF) has led, since 2014, to crucial impacts on production of recycled carbon fibre (rCF) materials. Substantial decreases in production cycle duration for a bestselling rCF thermoplastic prepreg product range – Carbiso TM – both enhanced its bulk production and cemented its commercial viability **[5.1]**. These improvements have aided ELGCF by accelerating both substantiative sales (GBP2,000,000 annually from 2018) as well as sizeable inward investment (a 25% shareholding). In turn, this accelerated company growth has driven concomitant environmental benefits from industrial usage of a recycled material as a feedstock.

Formed when German parent ELG Haniel acquired Recycled Carbon Fibre Ltd in 2011, ELGCF was the first and is still one of the largest recycling operations in the world for carbon fibre reinforced polymers (CFRPs). Their high-quality short rCF and non-woven long rCF mats are employed in a number of applications, including: bogie frames for railways; nacelles in wind energy turbines; car bonnets; undertrays and roofs for the automotive industry; and integrated circuit (IC) carrier trays for the electronics industry **[5.1]**. On the University's knowledge transfer into the company, the Managing Director (MD) of ELGCF says: "*The research undertaken by Professor Kerry Kirwan and his team has enabled ELGCF to become pioneers of sustainable CFRP recycling; without this research we would not have been able to achieve this success*" **[5.1].**

Impact on production: Recycling carbon fibre offers three distinct advantages over using new ('virgin') carbon fibre: lower cost (approximately 40% cheaper); security of supply (mitigating shortages of virgin fibre); and improved environmental sustainability (reducing waste bound for landfill and boosting re-use levels). However, rCFs are not a straightforward substitution for virgin fibres and converting them into a useable product is a lengthy and technically complex process.

Between 2014 and 2019 ELGCF worked closely with WMG on product development, addressing a number of challenges posed in rCF manufacturing. In particular, the long production cycles for the company's thermoplastic prepreg range (Carbiso TM) were an obstacle towards bulk sales, and the company was also seeking to improve processing parameterisation for its chopped ranges (Carbiso C, CT, CT+). Drawing on characterization work at Warwick (WMG) with different types of carbon fibres, and how they related to mechanical properties in laminates **[3.1]**, as well as how alterations to mould lay-up and curing affected the void volume fraction **[3.2]**, ELGCF's statement **[5.1]** reveals that these key technical challenges were addressed by:

- Optimising processing parameters for rCF fibre thermoplastic composites (Carbiso TM). "*Improvements were made through use of a stamping process that rapidly cooled the material down to just below the melting point in the mould by utilising a tool at a controlled temperature. Understanding what temperature should be used for the tool was vital as it ensured that there was no deformation in the parts post-processing*." This decreased production cycles from 10 minutes to just 2 minutes, a five-fold increase in productivity which greatly assisted production of the material in bulk and solidified its commercial prospects.
- Enhancing the processing of chopped rCFs. "*Work carried out by WMG allowed for greater understanding of the processing of short fibre chopped tow carbon fibres (Carbiso C, CT, CT+) through a compounding (a combination of extrusion and pelletisation) followed by injection moulding to produce thermoplastic composite materials. Specifically, conditions were optimised to reduce the damage caused by processing to the fibre and maximising the potential mechanical properties.*"

This was in addition to the development of design data and physical property characterisation of rCF/polymer compounds and resulting composites, giving an immediate idea of which processing changes could achieve optimum production results. All of these improvements facilitated the development and commercial viability of both the Carbiso C short fibre (C, CT and CT+) and Carbiso TM long fibre nonwoven product ranges, in addition to enabling mass production **[5.1]**.

Impact on commerce and the economy: As a consequence of improved production, annual sales have grown rapidly from GBP300,000 in 2016 to GBP2,000,000 throughout the years 2018 to 2020 **[5.1]** – representing an increase of greater than 560%, and minimum total sales of GBP6,600,000 between 2016 and 2020. Up to the end of 2020, Carbiso C, CT, CT+ and Carbiso TM accounted for 80% of the current financial value of ELGCF's total sales, citing the products as their bestsellers which are sold across 26 countries worldwide. Specific clients and applications include **[5.1]**:

- [text removed for publication]: "*[U]se of recycled carbon fibres (Carbiso C and Carbiso TM) to form the core of the carbon fibre composite cases of the* [text removed for publication] *laptops, saving weight compared to the glass fibre cores used in the previous generation and providing cost and environmental benefits compared to the use of virgin carbon fibre."* Approximately 300t of rCF from ELGCF is purchased by [text removed for publication] annually.

- [text removed for publication]: *"Use of recycled carbon fibres in thermoplastic compounds intended for use in the electronics industry."* Approximately 230t of rCF from ELGCF is purchased by [text removed for publication] annually.

Additionally, by the end of 2020 four further sales contracts for the Carbiso TM and C ranges were progressed with multinationals in the automotive and aerospace sectors [text removed for publication]. Growth in annual sales from fulfilment of these contracts is expected to be GBP4,300,000 in 2021 **[5.1]**, making ELGCF attractive to further investment during 2020 whilst also allowing for better strategic business planning based on this projected growth. In attracting both current sales and future sales contracts, WMG research was invaluable – with the scientifically robust analysis of the mechanical properties of rCF **[3.1]** as well as performance vs. cost methodologies **[3.2]** providing value for money reassurance and establishing that ELGCF's products could meet the tough demands of their clients' chosen applications **[5.1]**.

In April 2019, Mitsubishi Corporation acquired a 25% strategic shareholding in ELGCF **[5.2]**. Before the deal was finalised, WMG hosted representatives from the Japanese multinational to demonstrate the value of the department's research contributions and how they fit into ELGCF's overall strategy. On this investment the MD of ELGCF stated: "*WMG's unmatched capabilities in terms of industrial-scale processing within academia and long-standing links into key sectors such as automotive and rail has developed our unique offer – encompassing the key Carbiso TM and Carbiso C product (C, CT, CT+) ranges – and made ELG attractive in terms of inward investment from multinational companies*" **[5.1]**.

The combination of both volume sales and the investment from Mitsubishi has benefited the local economy (Coseley is approximately 30 miles from the Warwick campus) and supported expansion of the company's workforce. The number of people employed by ELGCF has increased from 42 in 2016 to 102 in 2020, comprising 50 production staff, 20 staff in maintenance, planning, supervisory, quality and EHS roles supporting production, 12 technical staff and 20 staff in management, sales and marketing and admin roles **[5.1]**.

Impact on the environment: Resulting from strong commercial interest and WMG enabling mass production of key product ranges, in 2020 ELGCF is producing at its max capacity of 1,700t annually while saving substantial waste from landfill **[5.1]**. Production at this level is inseparable from the environmental benefits, with rCF requiring only 500°C for pyrolysis (thermal breakdown) in contrast to 1,800°C for virgin carbon fibre manufacturing. Compared to the same levels of virgin carbon fibre production, ELGCF rCF product manufacture has a net saving of -280GJ/t in primary energy demand (PED) as well as -31tCO_2e/t in global warming potential **[5.1],** or a total saving of -476,000GJ/year and -52,700tCO_2e/year respectively for the 1,700t. This decrease of 52,700t in CO_2e is the equivalent to the greenhouse gas emissions from 11,385 passenger vehicles driven for a year, the CO_2 emissions from 58,000,000lbs of coal burnt, or the carbon sequestered from 68,824 acres of forest **[5.3]**. WMG has facilitated further green collaboration, such as incorporation of sustainable materials in the INEOS Team UK's America 2021 Cup build programme **[5.1]**.

Overall, the collaboration between WMG and ELGCF is prime example of superior industrial-facing research – solving specific production challenges to hasten commercial, economic and environmental benefits. As a closing statement the MD of ELGCF stated: "*Growth and inward investment on such a rapid timescale between 2016 and 2020 would have been impossible without input from the University of Warwick, accelerating ELGCF to world-leader status for carbon fibre recycling far sooner than would have occurred without this greatly valued collaboration*" **[5.1]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] Statement from the Managing Director of ELG Carbon Fibre Ltd
[5.2] ELG Carbon Fibre press release on 08/04/19 https://tinyurl.com/yxd6gxoa
[5.3] EPA Greenhouse Gas Equivalencies at 52,700tCO_2e https://tinyurl.com/84w4jn5s