Supporting information for

From aviation to aviation: environmental and financial viability of closed-loop recycling of carbon fibre composite

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1 Methodology

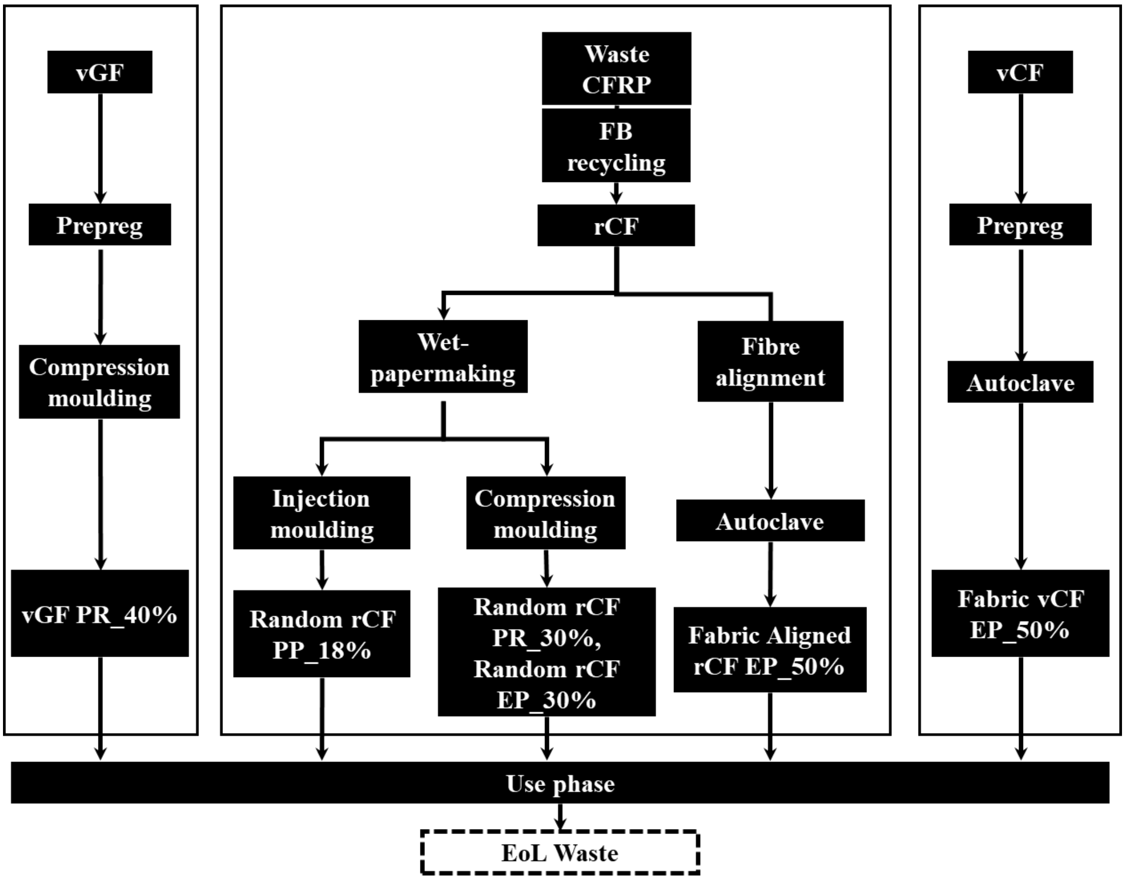


Figure S1 Overview of pathways and processes for manufacture of aircraft components from virgin glass fibre, recycled and virgin carbon fibre.

1.1 Mechanical properties of composite materials

1.1.1 Mechanical properties of random oriented rCFRP

For random oriented short fibres reinforced plates, the factor ζ can be calculated as summarized in **Table S1**. The theoretical calculation of mechanical properties of random oriented rCFRP have been validated by experimental measurements [1, 2].

Table S1**.** Traditional Halpin-Tsai parameters for random oriented short fibres reinforced plates.

E_{11}	$\zeta = 2(l/d) + 40{v_f}^{10}$	Longitudinal modulus
E_{22}	$\zeta = 2$	Transverse modulus

1.1.2 Mechanical properties of aligned rCFRP

A continuous, unidirectional fibre reinforced composite lamina is an orthotropic material. Based on the lamina theory[3], the Young's modulus and shear modulus of the composite can be calculated

$$E_1 = E_f V_f + E_m V_m \tag{1}$$

where E_1 is longitudinal Young's modulus.

$$E_2 = \frac{E_f E_m}{E_m V_f + E_f V_m} \tag{2}$$

where E_2 is transverse Young's modulus.

$$G_{12} = \frac{G_f G_m}{G_m V_f + G_f V_m} \tag{3}$$

where G_{12} is longitudinal Shear modulus.

The major Poisson's ratio (transverse contraction due to an axial extension) ν_{12} is defined as:

$$\nu_{12} = \nu_f V_f + \nu_m V_m \tag{4}$$

There is a relationship between the major Poisson's ratio ν_{12} and the minor Poisson's ratio ν_{21} (axial contraction due to a transverse extension) as below:

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2} \tag{5}$$

According to the stress-strain relations of materials for principal directions, the stiffness matrix $[C]$ is

$$[C] = \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$

The compliance matrix $[S]$ is

$$[S] = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & 0 \\ -\frac{\nu_{21}}{E_2} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$$

The coordinate transformation matrix is

$$[T] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta\ 0 & \cos^2\theta - \sin^2\theta \end{bmatrix}$$

where θ is the rotation angle about the origin.

The engineering-tensor interchange matrix $[R]$ is

$$[R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

Therefore, stiffness compliance matrices for an angled lamina can be expressed in terms of the stiffness matrix in the principal direction

$$[\bar{C}] = [T]^{-1}[C][T]^{-T} = [T]^{-1}[C][R][T][R]^{-1}$$

The multi-laminate composite used in this analysis is assumed to be 4 layers with each layer thickness of 0.5 mm in a layout$[0°/90°/0°/90°]$. Based on the Classical Lamination theory, the extensional stiffness matrix, coupling stiffness and the bending stiffness of the laminate can be calculated as follows:

$$[A] = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k (z_k - z_{k-1}) = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k t_k$$

$$[B] = \frac{1}{2}\sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k (z_k^2 - z_{k-1}^2) = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k t_k \bar{z}_k$$

$$[D] = \frac{1}{3}\sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k (z_k^3 - z_{k-1}^3) = \sum_{k=1}^{N} \left(\bar{C}_{ij}\right)_k (t_k \bar{z}_k^2 + \frac{t_k^3}{12})$$

$\left(\bar{C}_{ij}\right)_k$is the stiffness of the kth layer, t_k is the thickness of the kth layer, $\bar{z}_k$is the distance from the mid-plan to the centroid of the k^{th} layer. *A* is the extensional stiffness matrix, *B* is the coupling stiffness, *D* is the bending stiffness.

Based on the force-deformation relations [4], Young's modulus of the composite lamina is

$$E_1 = \frac{1}{t}(A_{11} - \frac{A_{12}^2}{A_{22}}) \qquad 6$$

$$E_2 = \frac{1}{t}(A_{22} - \frac{A_{12}^2}{A_{11}}) \qquad 7$$

$$E_2 = \frac{1}{t}(A_{22} - \frac{A_{12}^2}{A_{11}}) \qquad 8$$

$$\nu_{12} = \frac{A_{12}}{A_{22}} \qquad 9$$

$$\nu_{21} = \frac{A_{12}}{A_{11}} \qquad 10$$

$$G_{12} = \frac{A_{33}}{t} \quad (11)$$

Table S2**.** Mechanical properties of CF, epoxy resin.

	vCF, T300	rCF, T300	Epoxy resin
Young's modulus, E, GPa	227.80	217.79	5.00
Poisson ratio, v	0.22	0.22	0.30
Strength, σ, MPa	4240	4160	75
Shear modulus, G, GPa	93.36	89.26	1.92
Bulk modulus, k, GPa	135.60	129.64	4.17
Lateral compression modulus, K, GPa	166.72	159.39	4.81

1.2 Aircraft use phase

According to BADA model, fuel consumption for aircraft is expressed in Thrust Specific Fuel Consumption (TSFC) based on an energy balance of thrust.

$$T = D = \frac{1}{2}\rho V_{TAS}^2 A C_D \quad (12)$$

$$f = \eta \times T \times C_{fcr} \quad (13)$$

where T is the thrust, f is the fuel consumption for aircraft, D is the drag, A is the wing reference area, V_{TAS} is the true air speed, ρ is the air density, C_{fcr} is the cruise fuel flow correction coefficient (dimensionless), C_D is coefficient of drag, η is thrust specific fuel consumption which can be expressed as below:

$$\eta = C_{f1}(1 + \frac{V_{TAS}}{C_{f2}}) \quad (14)$$

where C_{f1} is 1st thrust specific fuel consumption coefficient C_{f2} is 2nd thrust specific fuel consumption coefficient

The coefficient of drag can be expressed:

$$C_D = C_{D0} + C_{D2}{C_L}^2 \quad (15)$$

where C_{D0} is the parastitic drag coefficient (cruise) (dimensionless ~0.02), C_L is the life coefficient (see Eq 20), C_{D2} is the induced drag coefficient (cruise) which is a function of C_L (see Eq 21).

$$C_L = \frac{2mg}{\rho {V_{TAS}}^2 A} \quad (16)$$

$$C_{D2} = \frac{{C_L}^2}{\pi A_R e} \quad (17)$$

where m is the weight of aircraft, A_R is the aspect ratio, e is the Oswald efficiency factor which is a function of the aspect ratio,

The true air speed of aircraft can be displayed as below:

$$V_{TAS} = (\frac{2}{\mu}\frac{p}{\rho}\left((1+\frac{(p_0)_{ISA}}{p}((1+\frac{\mu}{2}\frac{(\rho_0)_{ISA}}{(p_0)_{ISA}}V_{CAS}{}^2)^{\frac{1}{\mu}}-1)^{\mu}-1\right))^{1/2} \quad 18$$

where μ is the a factor (μ= (γ-1)/γ), γ is the isentropic expansion coefficient for air, p is the pressure at the flying altitude, $(p_0)_{ISA}$ is ISA pressure at sea level, $(\rho_0)_{ISA}$ is air density at sea level, ρ is air density above tropopause, V_{CAS} is calibrated air speed as expressed below:

$$V_{CAS} = a_0(5\left(\frac{P\ (1+0.2M^2)^{\frac{1}{\mu}}-1}{(P_0)_{ISA}}+1\right)^{u}-1)^{1/2} \quad 19$$

Where a_0 is sound speed at sea level, M is Mach number (the ratio of cruise speed and sound speed at sea level).

The BADA model is used to assess the fuel consumption flow for the whole plane. For component LCAs, we need to know the mass-induced fuel consumption of a component. The following calculation provided by [5] can be used to calculate the mass-induced fuel consumption of aircraft.

The total power required for a plane flying is the sum of the parasitic drag power and induced drag power,

$$P_{total} = P_{drag} + P_{lift} = \frac{1}{2}C_D\rho A_p v^3 + \frac{1}{2}\frac{(mg)^2}{\rho v A_s} \quad 20$$

where A_p is the frontal area of the plane, A_s is the cross-sectional area of sausage (the square of wingspan), C_D is the drag coefficient, ρ is the density of air, v is the speed of the plane, m is the mass of the plane and g is the gravitational acceleration.

The fuel efficiency is expressed as the energy per distance the plane travelled at speed v,

$$F_f = \frac{P_{total}}{\varepsilon v} = \frac{1}{\varepsilon}\left(\frac{1}{2}C_D\rho A_p v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}\right) \quad 21$$

where ε is the efficiency of real jet engine (~1/3)

The optimum speed is the speed when the lift-related drag force equals the drag force.

$$v_{opt} = \frac{mg}{\rho\sqrt{C_D A_p A_s}} \quad 22$$

Therefore, the expression of fuel efficiency can be altered into:

$$F_f = \frac{1}{\varepsilon}\left(\frac{C_D A_p}{A_s}\right)^{\frac{1}{2}}(mg) = \frac{1}{\varepsilon}(C_D f_A)^{\frac{1}{2}}(mg) \quad 23$$

where f_A is the filling factor (equals A_p/A_s)

Thrust is a force, which is energy per unit distance. The total energy used per unit distance is bigger by a factor (1/ε). The mass induced transport cost can be defined as the energy per unit weight per unit distance:

$$MIF = \frac{F}{m} = \frac{(C_D f_A)^{\frac{1}{2}}}{\varepsilon} g \quad 24$$

Table S3 Parameters for estimation of mass induced fuel consumption.

Type	Mass (fully-laden), m (kg)	Wingspan, w (m)	Frontal area, A_p (m^2)	Density, ρ (kg/m^3)	Drag coefficient, c_d	Optimum speed, v_{opt} (m/s)
Boeing 747-300	363,000	59.64	180	0.36	0.03	220

2 Results and discussion

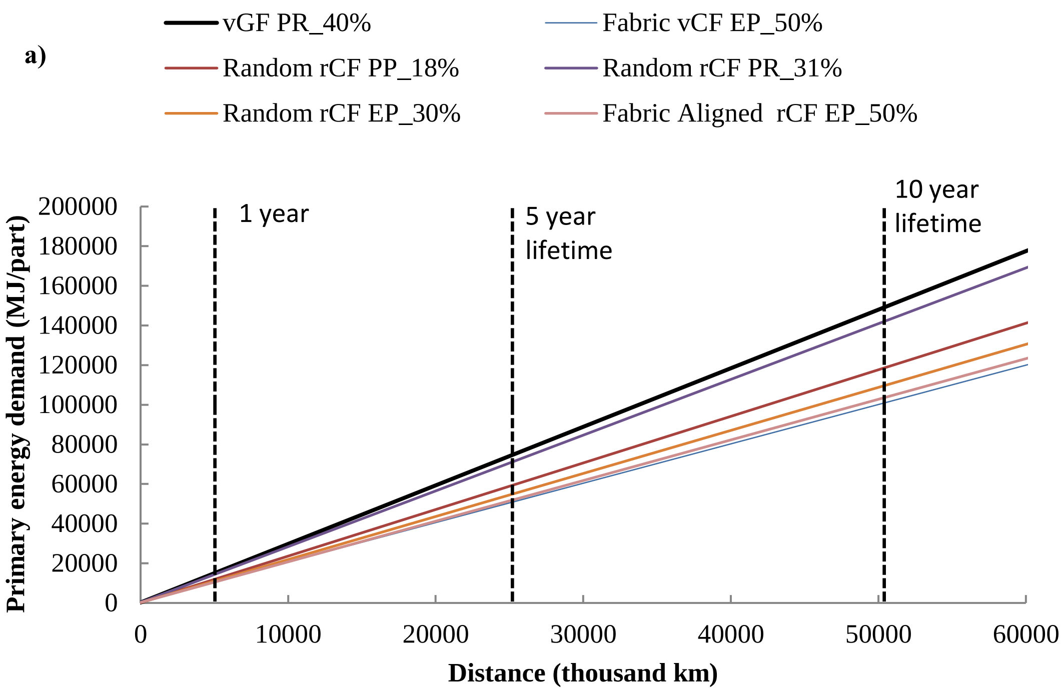
2.1 Mechanical properties of rCFRP

Table S4. Material properties of selected materials in the study.

Material	vGF PR_40 %	Fabric vCF EP_50%	Random rCF PP_18%	Random rCF PR_30%	Random rCF EP_30%	Fabric Aligned rCF EP_50%
Density, g/cm^3	1.77	1.50	1.17	1.42	1.38	1.50
Modulus, Gpa	23.0	70.0	16.3	14.2	37.1	60.8
Fibre volume fraction	40%	50%	18%	31%	30%	50%
Fibre weight fraction	58%	60%	30%	39%	39%	60%
Face thickness, mm	1.50	1.04	1.68	1.76	1.28	1.08
Core thickness, mm	12.00	12.00	12.00	12.00	12.00	12.00

2.2 Life cycle energy use and greenhouse gas emissions

a)



b)

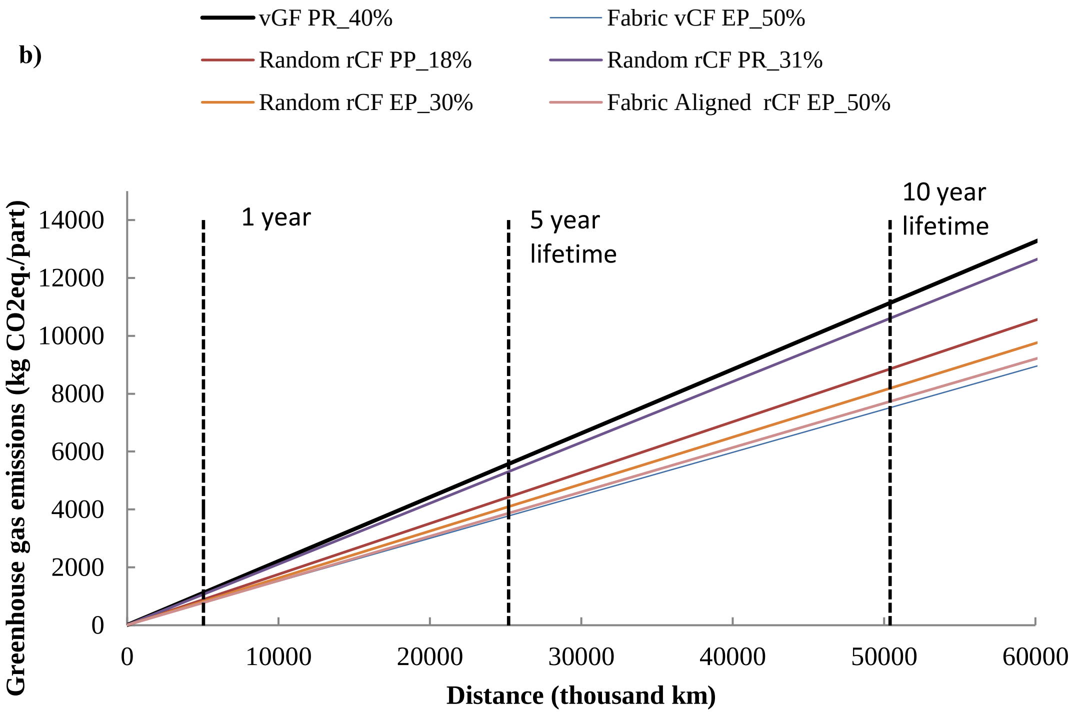


Figure S2 (a) life cycle PED (MJ/part) and (b) life cycle GHG emissions (kg CO_2eq/ part) as a function of the aircraft distance travelled.

2.3 Life Cycle Cost

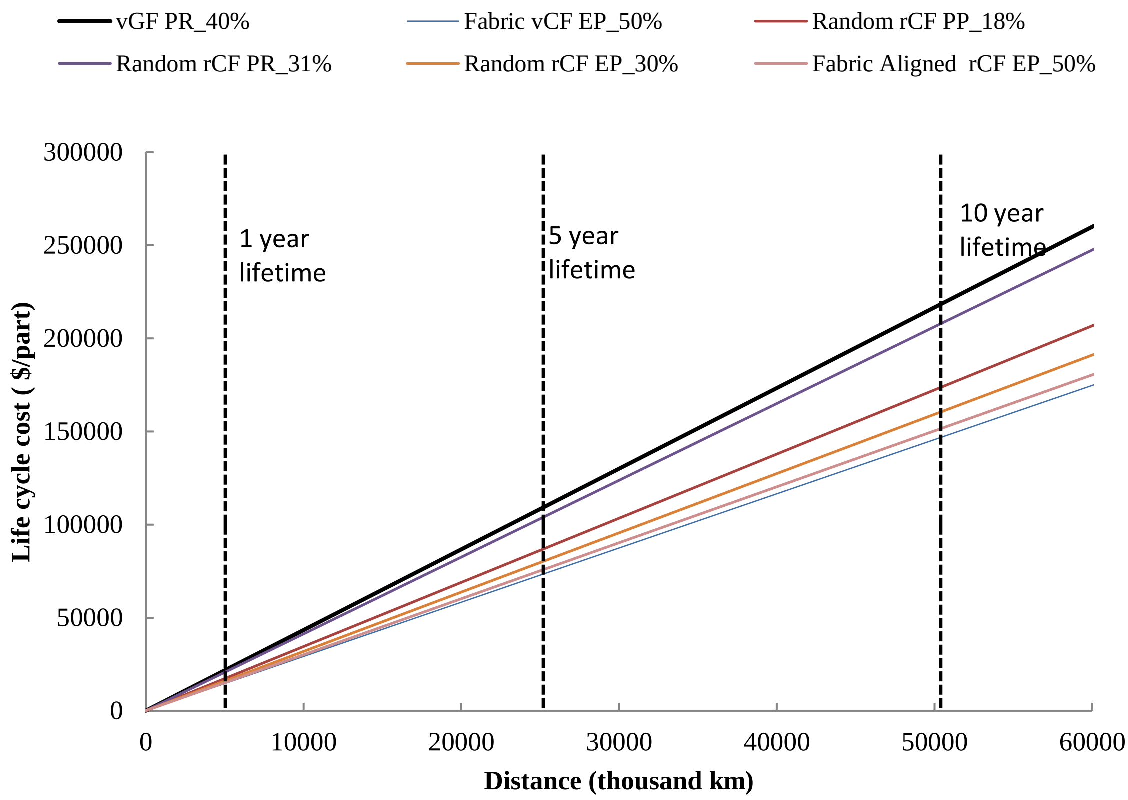


Figure S3 The life cycle cost of aircraft component materials ($/part) with varied life cycle distances.

3 References

[1] Wong KH, Pickering SJ, Turner TA, Warrior NA. Compression moulding of a recycled carbon fibre reinforced epoxy composite, In SAMPE 2009 Conference. Baltimore, Maryland, 2009.
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[3] Jones RM. Mechanics of composite materials: Scripta Book Company Washington, DC; 1975.
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