ENVIRONMENTAL IMPACT ASSESSMENT OF AVIATION EMISSIONS REDUCTION THROUGH THE IMPLEMENTATION OF COMPOSITE MATERIALS

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ABSTRACT

Purpose

Carbon fiber reinforced polymers (CFRP) have been developed by the aviation industry to reduce aircraft fuel burn and emissions of greenhouse gases. This study presents a lifecycle assessment (LCA) of an all-composite airplane, based on a Boeing 787 Dreamliner. The global transition of aircraft to those of composite architecture is estimated to contribute 20-25% of industry CO_2 reduction targets. A secondary stage of the cradle-to-grave analysis expands the study from an individual aircraft to the global fleet.

Materials and Methods

An LCA was undertaken utilising Sima Pro 7.2 in combination with Ecoinvent. Eco-indicator 99 (E) V2.05 Europe EI 99 E/E was the chosen method to calculate the environmental impact of the inventory data. The previously developed Aviation Integrated Model was utilised to construct a scenario analysis of the introduction of composite aircraft against a baseline projection, through to 2050, to model CO_2 emissions due to their particular relevance in the aviation sector.

Results and Discussions

The analysis demonstrated CFRP structure results in a reduced single score environmental impact, despite the higher environmental impact in the manufacturing phase, due to the increased fossil fuel use. Of particular importance is that CFRP scenario quickly achieved a reduction in CO_2 and NO_x atmospheric emissions over its lifetime, due to the reduced fuel consumption. The modeled fleet-wide CO_2 reduction of 14-15% is less than the quoted emission savings of an individual aircraft (20%) because of the limited fleet penetration by 2050, and the increased demand for air travel due to lower operating costs.

Conclusions

The introduction of aircraft based on composite material architecture has significant environmental benefits over their lifetime compared to conventional aluminum based architecture, particularly with regards to CO_2 and NO_x a result of reduced fuel burn. The constructed scenario analyses the interactions of technology and the markets they are applied in, expanding on the LCA. In this case, an observed fleet wide reduction of CO_2 emission of 14-15% compared to an individual aircraft of 20%.

KEYWORDS: aviation emissions, carbon fiber reinforced polymers, composite aircraft, global warming, life cycle assessment

1. INTRODUCTION

The combustion products of aviation fuel includes several gaseous emissions, mainly CO_2, nitrogen oxides (NO_x), water vapor (H_2O), sulphur oxides (SO_x) and soot; CO_2, NO_x and H_2O being greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC, 1999) have highlighted the potential impact of increased levels of greenhouse gases, both CO_2 and non-CO_2, on the global atmospheric environment. The aviation sector currently produces around 0.71 $GtCO_2$ (2%) of global energy related CO_2 emissions (IPCC, 2014). Though this is small in comparison to the transport sector (Duflou et al, 2009) as a whole 6.7 $GtCO_2$ (23%), aviation emissions are forecast to increase through to 2050 by around 3-4% per annum due to the increasing demand, approximately 5% per annum through to 2030 (Airbus, 2011; Boeing, 2013a), surpassing forecast improvements in fuel efficiency of 1-1.5% per annum (Kahn Ribeiro, *2007*). It is appreciated by the aviation industry itself that it is unacceptable to have an increasing share of global greenhouse gas emissions (IATA, 2009).

The aviation industry has a range of targets regarding the future control of carbon dioxide emissions, the main anthropogenic greenhouse gas under consideration, through to 2050. Targets include 1.5% per annum improvement in fleet fuel efficiency, carbon neutral growth from 2020 and a reduction in net CO_2 emissions of 50% by 2050 (ACARE, 2011; ICAO, 2013). Currently, the emission of greenhouse gases from the international aviation industry is unregulated and is not included in the scope of the Kyoto Protocol. Aviation is included in the European Union Emission Trading Scheme (EU ETS). International aviation emissions emitted in European airspace were temporarily covered by the EU Emissions Trading Scheme in 2012; at the time of writing, legislation has subsequently been withdrawn to allow the development of an international agreement and strategy to reduce international aviation emissions by the Iinternational Civil Aviation Organization (ICAO).

It is widely recognised that gaseous emissions at high altitudes are more environmentally damaging than those at ground level, due to increased interaction with gases in the atmosphere. A parameter used to quantify the effect of aviation emission is the Radiative Forcing (RF) Index, which is a measure of the impact of an agent on the energy balance of the earth's atmosphere. Aircraft operation involves the emission of (a) directly radiatively active substances (e.g. CO_2 or water vapor); (b) chemical species that produce or destroy radiatively active substances (e.g. NO_x, which modifies ozone concentration); and (c) substances that trigger the generation of aerosol particles or lead to changes in natural clouds (e.g. contrails). These emissions and cloud effects modify the chemical and particle microphysical properties of the upper atmosphere, resulting in changes in RF of the earth's climate system, which can potentially lead to climate change impacts and ultimately result in damage and welfare/ecosystem loss (Beck et al, 2009). Emissions of particulate materials can affect both the environment, contributing to climate change, and can be hazardous to human health, particularly if they are produced in the lower part of the atmosphere, around airports for example. Thus, it is important to analyse the life cycle of aircraft systems and structures in as much detail as possible, in order to understand the long-term impact on the human environment and the earth's ecosystem. However, on a global scale, CO_2 and NO_x emissions are greatest contributors to the global environmental impact, with the former contributing thousands of times more emissions than other products of fuel burning in aviation.

In addition to growing concern about the environmental impact of aviation, aviation fuel is the single most significant component of an airline operating cost, some 30-40% (IATA, 2009); this cost is highly dependent on a volatile oil price (EC, 2008). With profit margins for the financial year 2013/14 expected to be as little as 1.8% (IATA, 2012) cost control within the airline industry is highly important.

Carbon fiber reinforced polymer (CFRP), an advanced composite material, has been utilised as a structural component in the airframes of the 'next generation' of aircraft due to its reduced weight in comparison to aluminum. The Boeing 787 Dreamliner is a case in point, with 50% by weight consisting of composite materials. Airframe manufacturers claim that this next generation in airframe architecture can reduce fuel use, and subsequently CO_2, by around 20-25% (Airbus, 2012; Boeing, 2013b).

This study will provide an overview of the full LCA impact analysis and focus on the emission of CO_2 from the combustion of jet fuel. Whilst it is widely recognised that the combustion of jet fuel results in the emission of a range of pollutants, each with potentially detrimental atmospheric environmental impacts, CO_2 has been selected due to the importance placed on its emissions by the current policy, due to its long lifetime in the atmosphere.

The primary purpose of this study is to present a life cycle assessment of a section of a composite material aircraft, to understand the environmental impact on an individual aircraft scale. This data is further used to study the impact of the introduction of an aircraft with a composite material architecture on the projected global fleet emissions through to 2050. This combined simulation aims to model the effect of a transition in the global aviation fleet to the next generation of aircraft architecture. CO_2 and other environmental impacts are calculated using socio-economic scenarios from a set of integrated energy-economy-environment models against a baseline, and the results are subsequently discussed in relation to the industry targets and projections of potential savings.

The study is here presented in two distinct parts. Methods – Stage 1 present a full life cycle assessment of manufacturing, in-use and disposal stages of the composite and aluminium aircrafts, including the results from this part of the study (Results – Stage 1). Methods – Stage 2 presents the method and outputs of the Aviation Integrated Model scenarios, including the results (Results – Stage 2). Both stages of the analysis are integrated through the Discussion covering numerous aspects of this complex multidisciplinary analysis and the major findings are summarised in the Conclusions.

2. METHODS - STAGE 1

This paper is presented as a two-phase study; the method of enquiry of phase one is presented below and subsequently the results are presented. The secondary stage of analysis is presented *after* the LCA results.

2.1 LCA methodology and software

A Life Cycle Assessment is a method of quantifying the environmental impact of a product or service throughout its lifecycle from raw material extraction and processing, use phase and end of life disposal (ISO, 2006). The importance of LCAs is their ability to inform where environmental impacts occur and their relative importance. This enables interventions into the product life-cycle that are appropriate and prevent problem-shifting of either environmental products from one to another or shifting environmental impacts from one phase of a products lifecycle to another (Rebitzer, 2004).

A comparative LCA has been conducted on Section 46 of the Boeing 787 fuselage, due to the public availability of the manufacturing data required for LCA study. The Boeing 787 airframe was chosen due to the high proportion of CFRP utilised within its structure (approximately 50%) (Boeing, 2013b).

The LCA of fuselage section 46 of Boeing 787 was performed utilising Sima Pro 7.2 in combination with the Ecoinvent database. Ecoinvent contains industrial lifecycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services and transport services. Eco-indicator 99 (E) V2.05 Europe EI 99 E/E was the chosen method to calculate the environmental impact of the inventory data. This method enables the aggregation of different impact categories into a single score value, and thus allows a relative comparison between different environmental impacts to be conducted.

Technical data from the published literature has been utilised for the LCA where available (Boeing, 2013b; Beck et al, 2009). Due to commercial sensitivity associated with the technical design of the section and manufacturing processes, the research team, where appropriate, used informed judgment to estimate unavailable processes data. This pragmatic simplification of the LCA has been considered appropriate by the wider LCA literature (De Beaufort-Langeveld, 1997). Where appropriate, such assumptions are identified in this paper.

2.2 LCA scenarios

The LCA undertaken in this study is presented in two stages: the first stage compares the equivalent sections manufactured from CFRP and Aluminum alloy through manufacturing and disposal phases, and the second phase takes into consideration of the operational emissions, and hence the full life cycle,.

2.2.1 LCA data collection and system boundaries

A typical weight saving of 20% (widely reported by the industry) was used as the basis for comparison between the CFRP and Aluminum alloy structure (Campbell, 2004). Boeing 787 airframe consists of several one-piece CFRP tubesections. Section 46, being one of these tube sections, was manufactured by Alenia Aeronautica, Italy. The reported mass of Section 46 is 4000lb (1814 kg) (Norris, 2009). The total reported mass is assumed to include the fuselage skin, frames, stringers and floor beams. Due to the lack of specific data regarding the structure's geometric properties, the section is simplified to a uniform tube shape. The effective thickness of the uniform tube, calculated from the volume of the section and density of the material, is greater than the fuselage skin thickness of Section 46, to account for the additional parts. The simplified tube section was reported to be manufactured using a uniform automated tape laying manufacturing process.

The length and external diameter of the section are 33ft (10.06m) and 19ft (5.79m) respectively. The CFRP utilised in this study is assumed to have a density typical of the material, 0.0556lb/in^3 (0.0277 kg/cm^3). Applying the relationship between mass, as previously reported, and density, the effective thickness of the simplified tube fuselage wall was approximated at 12.95mm. This is a justifiable assumption, considering that the mass of the section will have the influence on LCA, rather than its dimensions.

Prior to the manufacturing consideration, the cradle LCA scope is defined by production of raw materials for each type of aircraft. CFRP consists of carbon fibres and epoxy resin. Carbon fibres are produced from polyacrylonitrile (PAN) based fibers through a process called the 'PAN process', during which the fibres are carbonised at temperatures between 1800 and 2700 °F (980 and 1480 °C). The aerospace grade CFRP utilised in manufacturing is assumed to be composed of 65% carbon fibre and 35% epoxy resin by weight, standard fractions in aerospace grade CFRPs. The pre-preg tape is placed onto a cylindrical mandrel using automated tape placement process and then cured in an autoclave. The layering process is repeated till the calculated fuselage wall thickness is achieved. The electricity consumption, and subsequent raw material consumption and emissions of electricity production, for the autoclave and pre-preg tape placement, via an Automated Fibre Placement machine, has been considered. A typical Italian electricity production mix has been considered.

The AFP robot used to manufacture Section 46 is manufactured by Ingersoll, with the energy consumption estimated to be at its maximum capacity of 16,000 kWh.

As a comparison, the section 47 and 48 of similar dimensions are manufactured by Vought, and cured in an autoclave with a power rating of 12,000 kW for a period of 8hrs, hence an estimated total energy consumption was 96,000 kWh.

The disposal of the composite section is assumed to be landfill. This assumption is discussed in greater details in the LCA results section. The parameters used in LCA of manufacturing of the composite section were intentionally chosen at the extreme end, in order to avoid any potential bias towards the utilisation of composite materials compared to their metallic counterparts. It was expected that the operational stage LCA would be overwhelmingly favourable towards utilisation of composites, due to the significant fuel savings and proportionally lower life cycle emissions.

2.2.2 LCA of aluminum alloy structure manufacturing

Two scenarios have been presented for the conventional aerospace aluminum alloy analysis and comparison. The buy-to-fly (BTF) ratio is the amount of metal utilised to manufacture a part, and this can be as high as 25:1 for aerospace components. For an average commercial aircraft the buy-to-fly ratio is estimated to be 8:1. Hence, two scenarios are presented below: Al Scenario 1, an idealised scenario with a buy-to-fly ratio of 1:1 and Al Scenario 2 with a more realistic and still Al favourable buy-to-fly ratio of 8:1. The two scenarios will be referred to as Al Scenario 1 and Al Scenario 2 respectively, and will be used here as the variables representative of the idealised and the standard manufacturing practice.

The mass of Al alloy utilised in the fuselage is estimated to be 25% more (Campbell, 2006) than the CFRP section, 2267kg. The aluminum ingots are hot rolled and subsequently machined into the final part. Recycling of aluminum is highly efficient requiring between 6-7% of the energy required for primary production (IEA, 2009). In current practice, recycled aluminum is not utilised in the production of aircraft parts. In SimaPro LCA software database, recycled aluminum is credited with positive emissions. The disposal scenarios for this analysis are assumed to be 100% recycling for aluminium in order to approach the generic lightweight advantage of CFRP with the most onerous comparison for CFRP case.

2.2.3 Additional consideration of in-use phase

As previously stated, LCA covers all phases of a product lifecycle from manufacture, use and final disposal. The following in-use analysis of Boeing 787 makes a number of initial assumptions; one, the aircraft has a range of 14,000km (Boeing, 2013b) and a life-span similar to a typical commercial aircraft of 30-years (Peel, 1995); two, the aircraft is assumed to operate daily, leading to the distance travelled by an aircraft during its lifetime of 150 million km.

For this stage of the analysis it is important to define the functional unit. The unit for comparison is tonne-km (tkm); the mass of the comparable unit multiplied by the distance travelled.

3. RESULTS – STAGE 1

3.1 LCA results – manufacture and disposal

Figure 1 shows the single score environmental impact for the three manufacturing and disposal scenarios considered in this study. The CFRP manufacturing scenario is demonstrated to have higher emissions than both Al Scenario 1 and Al Scenario 2, as expected, due to the higher energy power consumed during the carbon fiber production. The most significant contributor to the increased environmental burden is due to fossil fuel use, a parameter more evident in the normalisation plot of the environmental impact categories in Figure 2. The standard Eco-indicator values are dimensionless, similar to units of currency. In the Eco-99 system, the unit of measurement is called the Eco-indicator Point, Pt. The size of the Pt unit was chosen by Eco-99 to represent one thousandth of the annual environmental load of an average citizen in Europe.

The primary environmental impacts of concern within the aviation industry are the gaseous emissions of CO_2 and NO_x (ACARE, 2002; IATA, 2009), however other contributing factors are also analysed for a more complete understanding of the full environmental impact. Figure 3 quantifies the emissions of both gases through the manufacturing and disposal phase for the three material scenarios. The same trend as seen in the single score environmental impact is present here, with CFRP manufacturing being more environmentally burdensome, with respect to both CO_2 and NO_x.

3.2 LCA results – consideration of in-use phase

Figure 4 shows the single score environmental impact for the three full LCA scenarios considered in this study. The assessment demonstrates that the CFRP section results in a decreasing environmental impact when compared to both scenarios in Al alloy section analysis. Additionally, the environmental burden in the three scenarios is dominated by the consumption of jet-fuel in the in use phase, and in turn the environmental impact resulting from manufacturing and disposal can be considered negligible or insignificant in all the scenarios, as shown in our earlier study (Scelsi et al, 2011).

As previously, the emissions of NO_x and CO_2 are presented separately (Figure 5). The CFRP section results in a significant decrease in the emissions of both gaseous substances, 19% and 20% respectively.

3.2.1 LCA break-even distance/time

An additional stage of analysis undertaken by this study determined the distance and the hours of operation of an aircraft at which the CFRP section becomes environmentally beneficial. As demonstrated in the previous section, it is in the 'in-use' phase that the CFRP reverses the environmental deficit of production and disposal stage; the amount of hours of operation can be estimated. By negating the ascent and descent stages of the aircraft flight-path and assuming that the aircraft operates at a cruise speed of 950km/h (Boeing, 2013b) the operation time can be determined. The cumulative single score impact of three modeled scenarios calculated the break even distances for CFRP against Al1 and Al2 as 190,000km (210 hrs in operation) and 75,000km (83 hrs) respectively. Likewise, break-even distances for both CO_2 and NO_x were calculated (Table 1).

The results imply that the break-even point in the emissions consumption and savings is achieved after only a few international flights, and the manufacturing emissions can be hence neglected in the analysis of the global impact of aviation in the atmospheric emissions. The fuel consumption savings play a far more important part in achieving the emissions savings in the future air transport.

4. METHODS – STAGE 2

4.1 The AIM aviation systems model

As previously highlighted, the introduction of composite material aircraft has been identified as a method of achieving long-range industry targets for carbon emission reduction (IATA, 2009). The motivation in the aviation industry to introduce composite material aircraft is for both environmental and economic factors (Mason, 2007). The second stage of this study considers the impacts of a transition of the global aviation fleet to composite aircraft models with the aim of understanding how the aircraft variants are adopted in the global market and how the resulting carbon emissions reductions compare to those estimated per-aircraft as above (Helms & Lambrecht , 2007; Givoni & Rietveld , 2009).

This study utilises a previously developed model, the Aviation Integrated Modelling (AIM) (Reynolds, 2007), to simulate global aviation system responses to changes in costs and available technologies. AIM consists of seven interconnected modules modeling demand for air travel, routing and scheduling, airline costs and technology adoption, flight routing and emissions, local and global emissions impacts and regional economics, run iteratively until equilibrium between demand and supply is reached. For this study we concentrate on CO_2 and neglect the local emissions and regional economics modules.

AIM requires internally consistent scenarios of future population, gross domestic product (GDP) and oil prices to project demand and technology adoption. For these scenarios we use the outputs of three integrated assessment models used for a U.S. climate change mitigation study

(Clarke et al, 2007): IGSM (Integrated Global System Model), MERGE (Model for Evaluating the Regional and Global Effects) and MiniCAM (Mini-Climate Assessment Model), shown in Table 2. Two technology scenarios were constructed: a baseline analysis, in which current airframe technology continues to be used, and a second scenario where aircraft models utilising composite materials technology are introduced.

The commercial aviation fleet is assumed to consist of three representative aircraft variants. The defined aircraft variants have been determined by size with aircraft representing small (narrow-body, short to medium range), medium (wide-body, medium to long range) and large (wide-body, medium to long range) aircraft. The three aircraft variants are deemed to be representative of the overwhelming majority of commercial aircraft classes as represented in industry literature (Airbus, 2011; Boeing, 2013a). Table 3 summarises the physical characteristics and relative performance of the reference conventional and composite aircraft variants.

The composite material aircraft proposed for all size classes are assumed to be a suitable substitute for 100% of the aircraft fleet of that category. The size class defined as large includes those aircraft deemed very large, e.g. Airbus A380. The proportion of aircraft in the very large class is only 5% of new passenger aircraft delivered in the period 2011-2030 (Airbus, 2011) and is therefore not defined separately.

To better isolate the impact of composite materials, the modeling only considers the effect of a transition in airframe technology and associated evolutionary improvements in engine technology, from those used in the reference aircraft to composite material variants. The model does not take into account any technology transition in aircraft engine technology (e.g. open-rotor engines), the use of biofuels, operational changes relating to air transport movements

(ATMs) or the introduction of emission trading. In addition, we do not consider the next generation of aircraft after those modeled. For these reasons, total emissions are likely to err on the high side of those achievable.

5. RESULTS – STAGE 2

5.1 AIM results

As discussed above, two technology scenarios are modeled for each of the three socio-economic scenarios:

I. Reference simulation – continuation of conventional technology, and
II. Availability of composite material aircraft.

The primary driver for the adoption of composite material aircraft is the oil price, which influences whether fuel-saving technologies will be cost-effective (Table 2).

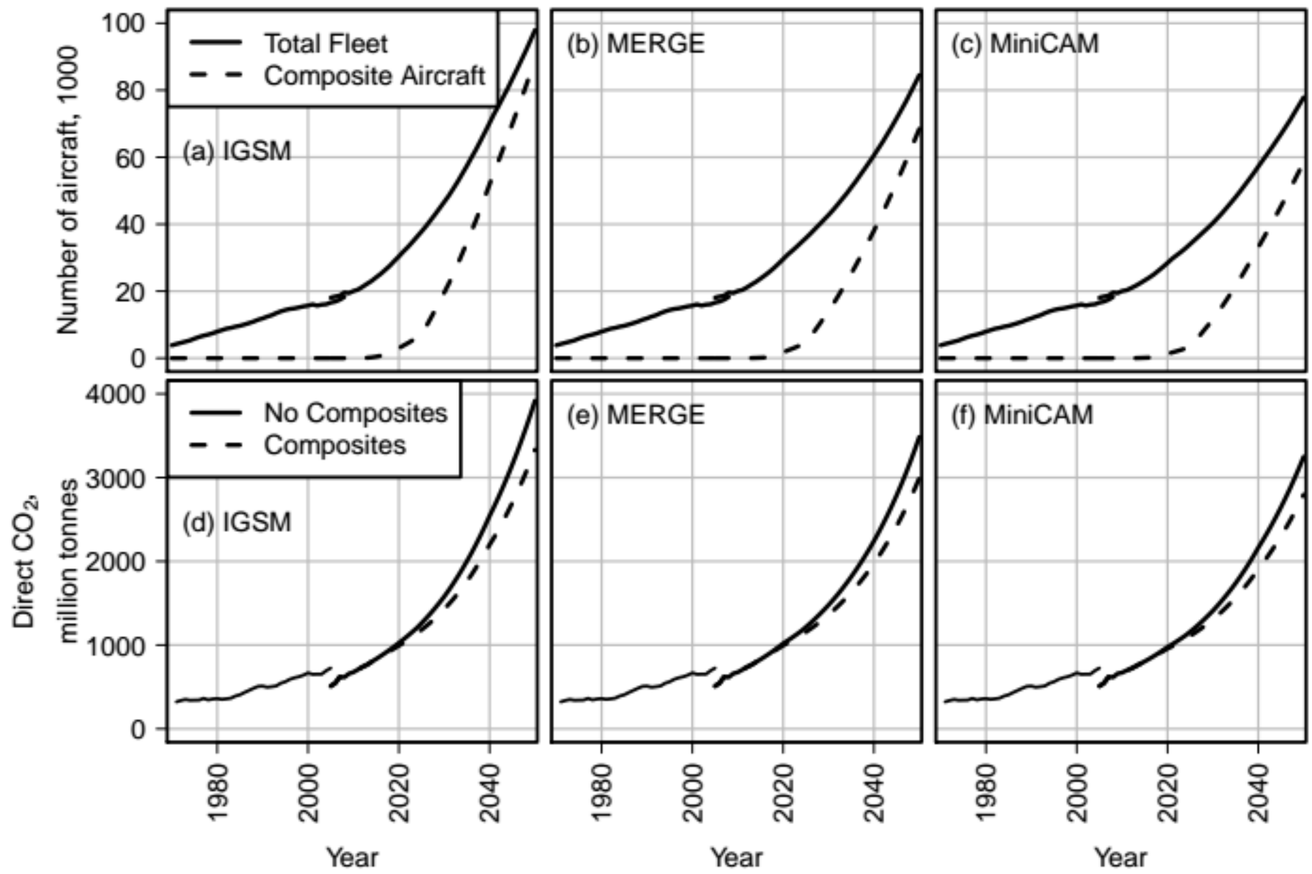

Figure 6 (a, b and c [top row]) shows the total number of aircraft in the global fleet and the proportion of composite aircraft. The total size of the fleet by 2050 is predicted to be between 95, 000 and 77, 500 aircrafts. In all three socio-economic scenarios by 2050 composite material aircraft compose the majority of the aviation fleet but did not achieve 100% penetration. Fleet penetration is dependent upon rates of fleet growth with time, which depend in turn on GDP and population projections, and the relative oil price modeled in each scenario. The high uptake of composite material aircraft in all scenarios indicates that they are cost-effective to operate in all cases modeled.

Figure 6 (d, e and f [bottom row]) shows the modeled CO_2 emissions of the global aviation fleet through to 2050 for each of three socio-economic scenarios utilised in this study. Historic global aviations emissions (pre-2005) collected by the International Energy Agency (IEA, 2007a;

IEA, 2007b) are plotted in addition to the simulation. CO_2 emissions are predicted to be reduced by between 14-15% by 2050 due to the introduction of composite aircraft, relative to the baseline scenario. It should be noted that the observed discrepancy between the AIM and IEA values is due to the fact that the IEA figures include *all* aviation, whereas AIM models 95% of scheduled passenger revenue passenger kilometres RPKs. AIM does not account for freight and unscheduled flights (Reynolds, 2007). Table 4 presents the numerical values for each scenario output in this analysis, showing absolute values for the aviation fleets with and without the implementation of composites.

6. DISCUSSION

6.1 LCA

The results of the LCA clearly highlight that the environmental impact of an aircraft is dominated by the in-use phase. The reader should note the difference in scale between the single score environmental impact of Fig. 1 (manufacturing and disposal phases) and Fig. 4 (inclusive of in-use phase) being measured in kPt and MPt respectively. Despite an increased environmental burden through the utilisation of CFRP at the manufacturing and disposal stage, particularly as a result of fossil fuel use, this is negligible when taken into consideration with the in-use phase.

The LCA scenarios presented for conventional aluminum airframe architecture (AL1 and AL2), present onerous comparison for the CFRP. The assumption of a 100% recycled waste disposal route reduced the single score environmental impact of both scenarios, due to this being deemed a positive impact in SimaPro LCA software. The disposal route for CFRP is assumed to be landfill, due to the lack of current recycling routes for a relatively new and novel material (Pickering, 2006; Witik, 2013)

6.2 Global Aviation

The benefits of a transition of the global passenger aviation fleet to composite material aircraft goes beyond the direct 14-15% CO_2 savings predicted in this study. The benefit of composite material aircraft implementation also includes globally reduced fuel consumption and therefore potentially lower direct operating costs, due to an improved lift-to-drag ratio and reduced weight. The reduction in fuel consumption leads to reduced CO_2 emissions and in addition reduced emissions in *all* combustion products (including NO_x and water vapour). The reduction in engine combustion products is more beneficial than a targeted intervention solely aimed at a net reduction in CO_2 emissions, for example the introduction of biomass derived jet fuel.

The industry target of CO_2 reduction by 50% on a RPK basis by 2020 cannot be achieved solely by the introduction of airframes utilising a high proportion of composite material, as demonstrated in this study. Though this novel lightweight technology is an important component in reducing the environmental impact of aviation, it is a step change in technology that must be considered in conjunction with a range of other technological and operational improvements.

The Advisory Council for Aviation Research and Innovation in Europe (ACARE,2002) goal of reducing fuel consumption per RPK by 50% for new aircraft entering service after 2020 is split between technological improvements in engine and airframe technology, 15-20% and 20-25% respectively. The remainder of 50% reduction is to be achieved through improvements in operational procedures air transport movements (ATM). Long-term ACARE goals through to 2050 include 75% reduction in CO_2 emissions per passenger kilometer relative to 2000

(ACARE, 2002). The composite aircraft utilised in this study achieves the primary goal for a reduction in fuel consumption for aircraft entering the fleet post-2020. To achieve the long-range goals of a 75% reduction would require a step change in aircraft design towards a blended wing body aircraft, which presents significant technical challenges, and technology readiness is predicted around 2037-38 (Vera Morales, 2011).

Greenhouse gas emissions from international aviation have not been included in the previous international programmes to tackle global warming and anthropogenic climate change. The inclusion of international aviation in the European Union Emissions Trading Scheme (EU ETS) in 2012 has since been suspended pending the formation of an international agreement at the 2014 ICAO annual general meeting. Calls from within the aviation industry are for single market based mechanism (MBM) that "... should contribute towards achieving global aspirational goals" (ICAO, 2011). Presently no MBM has been developed.

The lifetime of an aircraft airframe can be up to 30-years (Kahn Ribeiro, 2007) and those aircraft models entering service before 2020 could very well still be in operation by 2050, the end of the modeling period used in this study. The predicted growth in aviation demand to 2030 alone will require the delivery of between 27, 000 and 33, 500 new passenger aircraft (Airbus, 2011; Boeing 2013) equating to an order value of approximately $4 trillion. As was highlighted in this study the emission reduction potential of composite aircraft was limited due to fleet penetration not being 100% by 2050.

Despite an increased environmental impact of CFRP during manufacture and disposal, the section under analysis demonstrates a significant reduction in impact over its lifetime. The reduced impact is due to the in-use phase and consumption of jet-fuel that far outweighs the impact of manufacture and disposal.

Under all three socio-economic scenarios utilised in this study, the potential reduction in emissions of carbon dioxide due to a transition of the aircraft fleet to composite materials was 14-15% compared to a baseline projection using current technology in 2050 – a reduction in cumulative 2010-2050 emissions of 9-11%. Reductions in the emission of carbon dioxide is less than the quoted technical potential of 20-25% due to fleet penetration not being total and a passenger and service demand increase of 6-9% by 2050; the result of reduced operating costs of composite material aircraft resulting in lower ticket prices.

7. CONCLUSIONS

The life cycle assessment demonstrates a reduction in the environmental impacts through the transition of airframe architecture from conventional aluminum to CFRP. It was shown that CFRP was preferable even in the most favorable aluminum scenario (low buy-to-fly ratio and waste 100% recycled). Furthermore, the study highlighted how the life cycle environmental impact of aircraft is dominated by the in-use phase, particularly the consumption of fossil fuels and the release of CO_2 and NO_x related to the combustion of aviation fuel.

The conventional LCA presented in this study supported industry claims of a reduction in carbon emissions through the introduction of composite material airframe architecture. However, the secondary analysis, utilising the AIM model, demonstrates the potential reduction in carbon emissions were less than predicted due to an interaction of technology and market, in this case a positive rebound in demand due to lower ticket prices.

The conclusions of this study highlight the importance of creating a market based mechanism for carbon dioxide that supports the market adoption of more fuel efficient aircraft but also addresses potential uplift in demand as a result of the reduced operational costs of composite material aircraft. The results of this study were based on a simplified CFRP tube section, due to the lack of technical process data in the public arena. It is recommended that additional study should be undertaken with more detailed manufacturing process data and structural airframe components, both of CFRP and aluminum. An extension to this study would be to conduct a hybrid LCA to estimate indirect and direct emissions from the wider supply chain.

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8. TABLES

Table 1. Break-even distances and time (hours of flying) for CFRP vs. Al1 and Al2.

	CFRP vs. AL1		CFRP vs. AL2	
	Distance (km)	Time (h)	Distance (km)	Time (h)
Carbon dioxide	170 000	188	95 000	105
Nitrogen oxides	90 000	99	70 000	77

Table 2. Socio-economic model inputs into the Aviation Integrated Model (AIM).

Input	Scenario	USA	Western	Eastern Europe/Former	China	India	Japan	Africa/Latin America/Rest

Parameter			Europe[a]	Soviet Union				of the world
Population growth rate %/year[b]	IGSM	0.6	-0.2	-0.3	0.3	0.9	-0.2	1.3
	MERGE	0.4	0.0	-0.1	0.3	0.7	0.0	1.1
	MiniCAM	0.6	0.0	-0.1	0.2	0.8	-0.2	1.2
GDP/capita growth rate, %/year[b]	IGSM	2.2	2.9	4.0	4.0	2.5	3.1	1.9
	MERGE	1.4	1.7	3.4	4.5	4.3	1.3	2.5
	MiniCAM	1.3	1.0	3.3	5.1	4.8	1.2	1.9
Oil price, \$2005 per bbl	IGSM	106 (2020), 154 (2040)						
	MERGE	82 (2020), 124 (2040)						
	MiniCAM	74 (2020), 92 (2040)						

[a] The country composition of geographic regions in each socio-economic are different and as such a direct comparison of values is limited. Full country lists are presented in (Clarke et al, 2007)

[b] Mean values for 2005-2050 (Clarke, 2007)

Table 3. Substitute aircraft utilised and their operational performance.

Size Class	Large	Medium	Small
Definition (No. Seats)	>299	190-299	100-190
Reference Aircraft	Boeing 777-300	Airbus A330-300	Airbus A319-131
Reference Engine	Rolls Royce Trent 895	General Electric CF6 80E1 A2	V2511
Composite Aircraft	A350-1000	Boeing 787	TOSCA composite aircraft
Year of Fleet Entry	2017	2012[a]	2025[b]
Purchase Price (\$m)	205.8[b]	148.7[c]	67.0[b]
Maintenance Cost	30% lower than reference aircraft[d]		
Fuel Use (against reference aircraft)	25% lower[e]	20% lower[f]	22% lower[b]

Notes

[a] Closest full year of operation. First fleet entry late-2011.

[b] TOSCA mid-range estimate (Vera Morales, 2011)

[c] Average of Boeing 787 subtypes. Assumed 20% discount from list price

[d] TOSCA estimate. Boeing 787 factsheet relative to ‘comparable aircraft types’ (Boeing, 2013b)

[e] Airbus 350 factsheet relative to ‘current competitor’ (Airbus, 2012)

[f] Boeing 787 factsheet relative to ‘comparable aircraft types’ (Boeing, 2013b)

Table 4. A summary of the outputs for each scenario in AIM analysis.

Output Parameter	Scenario	2005 value	2020 value		2050 value	
			No Composites	Composites	No Composites	Composites
Direct CO_2, Mt	IGSM	510[a]	1025	993	3917	3333
	MERGE		1019	996	3485	2994
	MiniCAM		976	957	3247	2796
Direct CO_2, Mt per pkm[b]	IGSM	0.135	0.125	0.118	0.127[c]	0.100
	MERGE		0.125	0.120	0.127	0.103
	MiniCAM		0.125	0.121	0.127	0.105
Global fleet, number	IGSM	18100	29900	30400	92000	97900
	MERGE		29400	29600	80300	84500
	MiniCAM		28200	28400	74600	77800

[a] IEA (2007) give global direct aviation CO_2 in 2005 as 725 Mt; this includes freight and unscheduled flights which are not modelled in AIM.

[b] Since freight is not directly modelled in AIM, we use passenger kilometers (pkm) as a basis for comparison rather than tonne-kilometres (tkm) here.

[c] The rise in CO_2 per pkm reflects changing use patterns of aircraft; for a given individual flight emissions in this scenario are similar to those in 2020.

9. FIGURE CAPTIONS

Figure 1 Single score environmental impact comparison of the three scenarios: Al1 (BTF ratio 1:1), Al2 (BTF ratio 8:1) and CFRP section in manufacturing and disposal phase.

Figure 2 Normalization plot of environmental impact for the three scenarios by impact category.

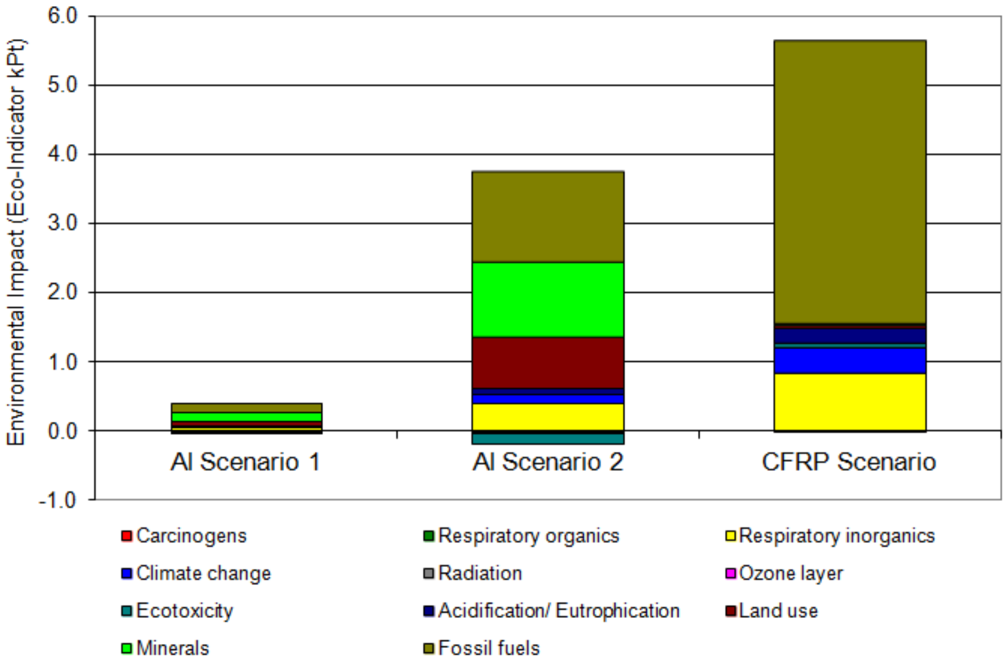
Figure 3 Quantities of CO_2 and NO_x produced in manufacturing and disposal of composite airframe section.

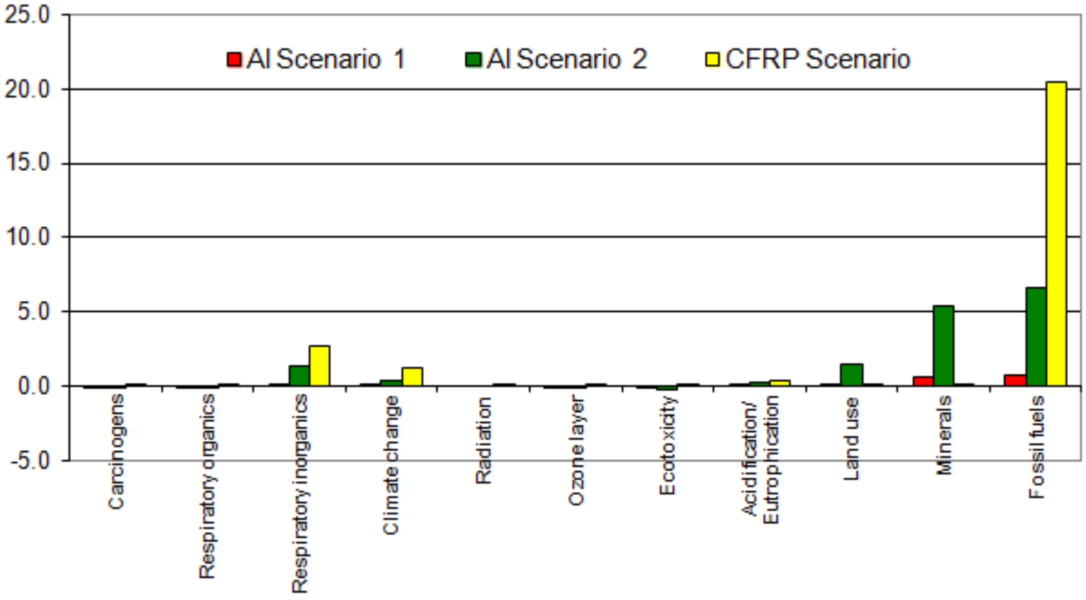
Figure 4. A complete LCA single score environmental impact comparison of the three scenarios used in this study.

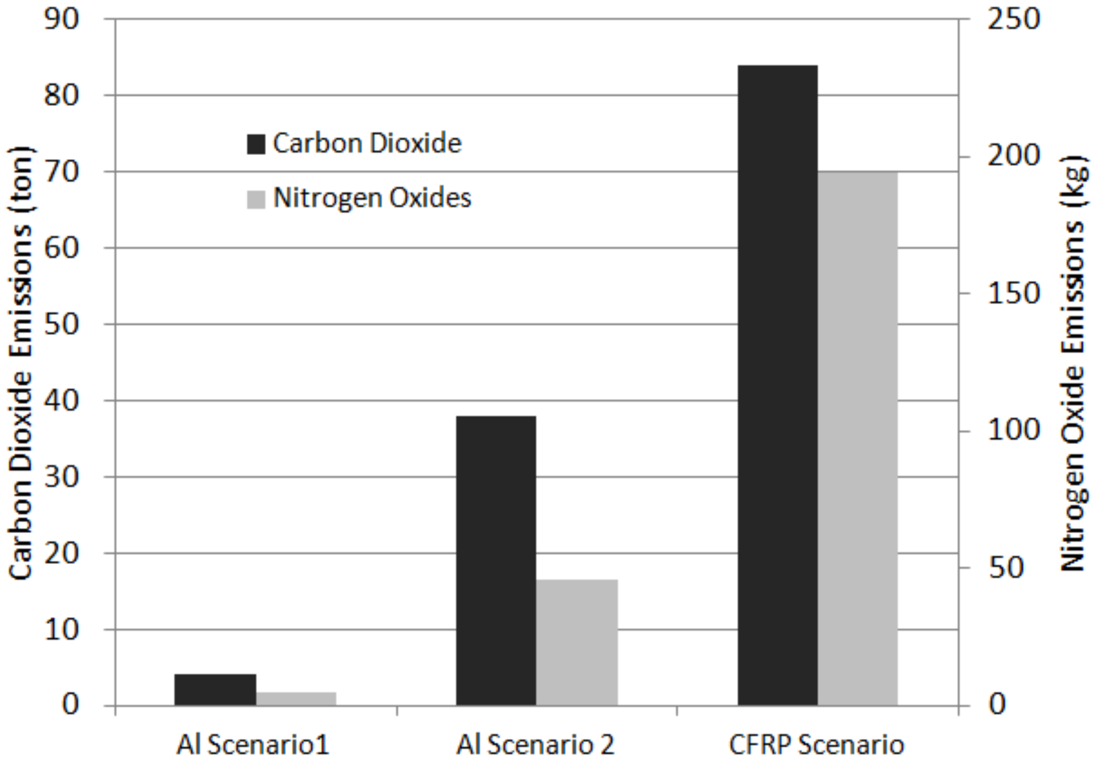
Figure 5. Quantities of CO_2 and NOx produced from the complete LCA of the three scenarios used in this study.

Figure 6 Modeled fleet penetrations of composite aircraft (top). Modeled emission of CO_2 through to 2050 (bottom).

10. FIGURES

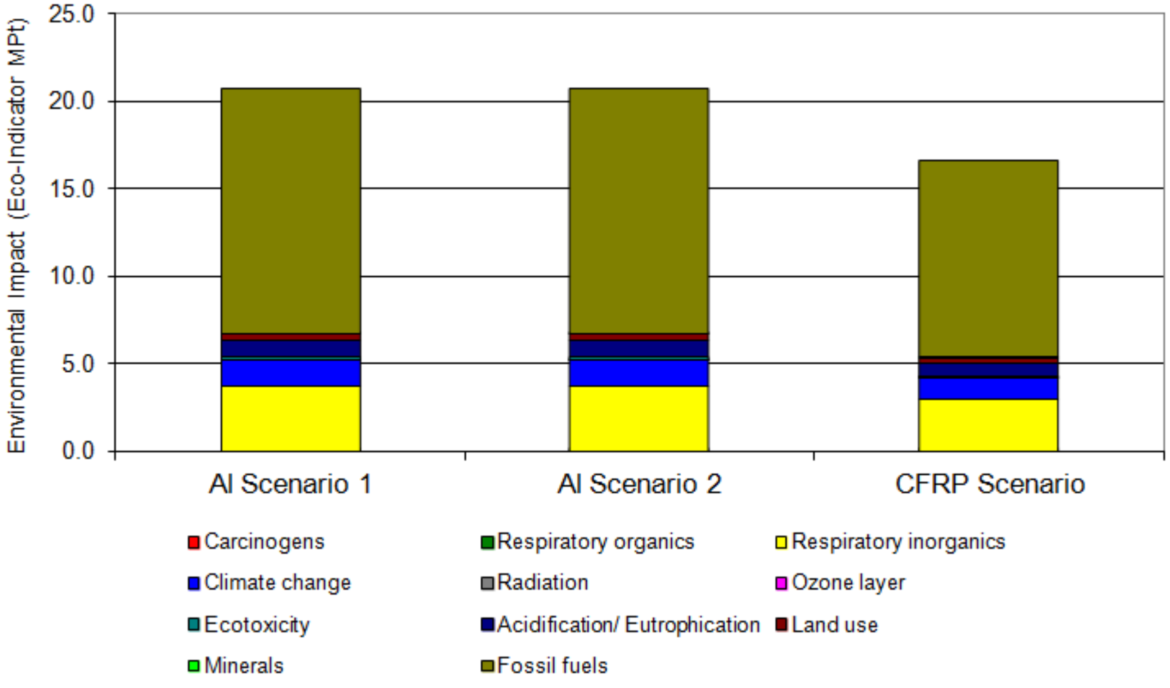

6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
Environmental Impact (Eco-Indicator kPt)
Al Scenario 1
Al Scenario 2
CFRP Scenario
Carcinogens
Respiratory organics
Respiratory inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Minerals
Fossil fuels


25.0
20.0
15.0
10.0
5.0
0.0
-5.0
Al Scenario 1
Al Scenario 2
CFRP Scenario
Carcinogens
Respiratory organics
Respiratory inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Minerals
Fossil fuels



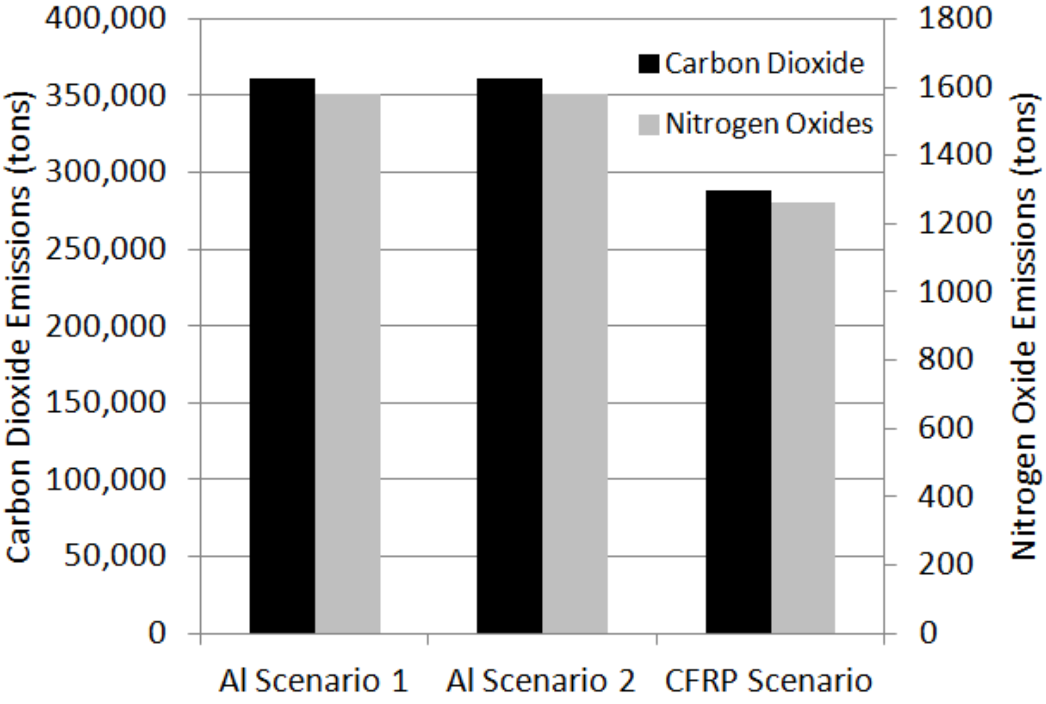
Carbon Dioxide
Nitrogen Oxides
Carbon Dioxide Emissions (ton)
Nitrogen Oxide Emissions (kg)
0
10
20
30
40
50
60
70
80
90
0
50
100
150
200
250
Al Scenario1
Al Scenario 2
CFRP Scenario

566

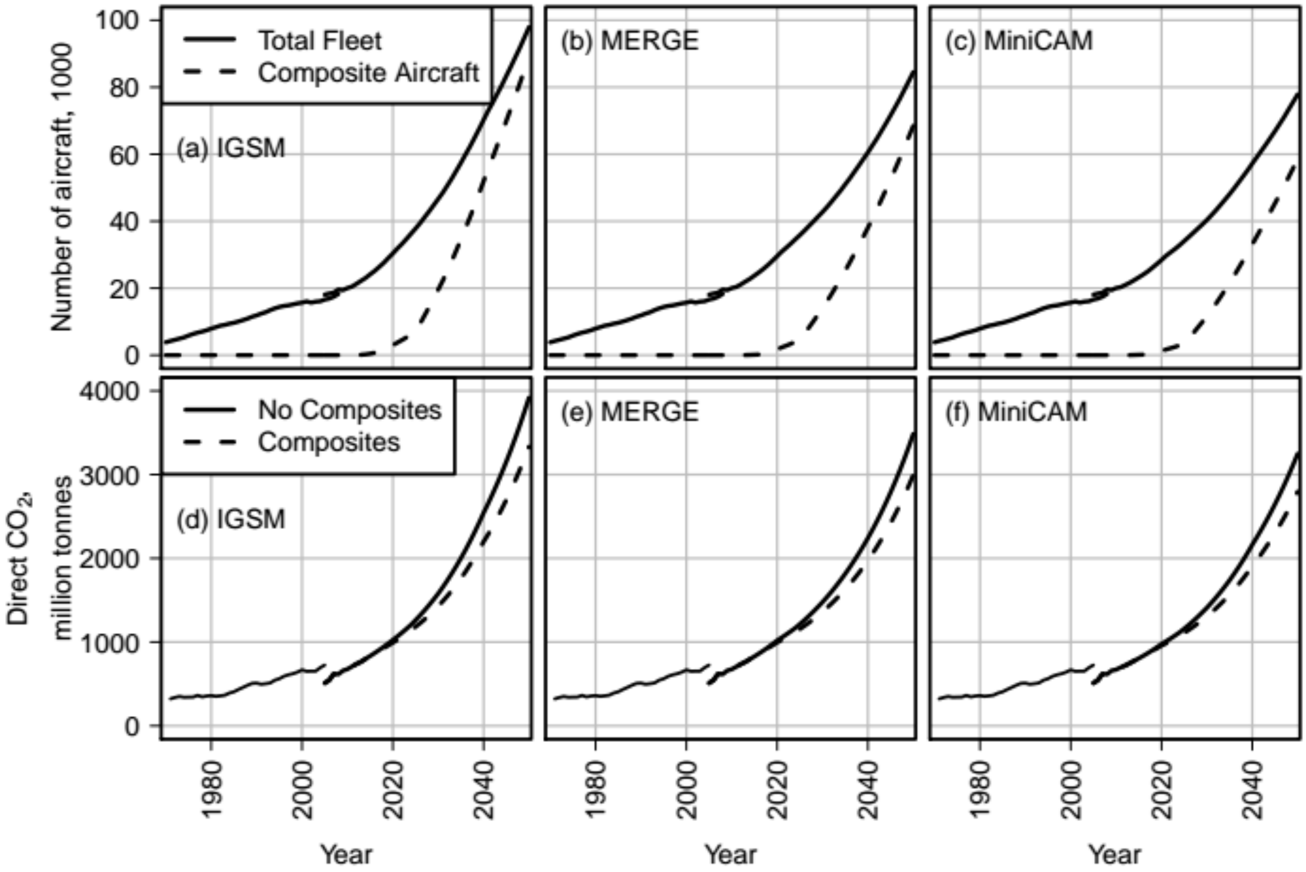


Environmental Impact (Eco-Indicator MPt)
0.0
5.0
10.0
15.0
20.0
25.0
Al Scenario 1
Al Scenario 2
CFRP Scenario
Carcinogens
Respiratory organics
Respiratory inorganics
Climate change
Radiation
Ozone layer
Ecotoxicity
Acidification/ Eutrophication
Land use
Minerals
Fossil fuels

567


400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Carbon Dioxide Emissions (tons)
1800
1600
1400
1200
1000
800
600
400
200
0
Nitrogen Oxide Emissions (tons)
■ Carbon Dioxide
■ Nitrogen Oxides
Al Scenario 1
Al Scenario 2
CFRP Scenario

568


Number of aircraft, 1000
100
80
60
40
20
0
Total Fleet
Composite Aircraft
(a) IGSM
(b) MERGE
(c) MiniCAM
Direct CO_2, million tonnes
4000
3000
2000
1000
0
No Composites
Composites
(d) IGSM
(e) MERGE
(f) MiniCAM
1980
2000
2020
2040
Year

569