



# Apportioning aviation CO<sub>2</sub> emissions to regional administrations for monitoring and target setting

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## ABSTRACT

Delivering reductions in greenhouse gas emissions from the aviation sector requires support and action from all tiers of government. There has been considerable focus on the policies that can be implemented at international and national levels; however, sub-national bodies can also play an important and influential role. In order to identify what this role may be, it is important for sub-national governments to have an understanding of the size of their potential emissions responsibility. At present there is no widely accepted methodology for the apportionment of either international or domestic aviation emissions to sub-national levels. This paper assesses a number of existing consumer- and producer-based CO<sub>2</sub> apportionment regimes that could be used to allocate the emissions from aviation to regional and other sub-national levels. This is followed by the presentation of a new hybrid consumer–producer apportionment regime applicable to aviation. This new approach is designed to provide an emissions baseline for a region that reflects its share of responsibility for the UK's aviation emissions as both a producer of emissions and consumer of the services provided by aviation.

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## 1. Introduction

In the year 2000, emissions from international aviation represented approximately 2.4% of global CO<sub>2</sub> emissions (Fuglestad et al., 2008). This already significant global emissions burden can, when allocated to nations according to the origin of each flight, represent an even higher and growing proportion of the national emissions burden (Bows and Anderson, 2007; Den Elzen et al., 2007; Jackson et al., 2007). The importance of aviation as a source of emissions has been recognised by the UK's Committee on Climate Change, which in response to the Climate Change Act 2008 has recommended that international aviation emissions are included in the country's 80% reduction target by 2050 (CCC (Committee on Climate Change), 2008).

The delivery of the UK's climate change strategy will require support at all administrative levels if it is to succeed in delivering the radical and urgent scale of emission reductions set out by the Climate Change Committee (CCC, 2008). Furthermore, due to the relationship between CO<sub>2</sub> and fossil fuel use, within all

fuel consuming sectors, those involved in the production of goods and services as well as their consumers (sometimes referred to as end or final users<sup>1</sup>) have a role to play in reducing CO<sub>2</sub> emissions

The paper focuses on the allocation of CO<sub>2</sub> emissions from aviation; however, we recognise that other aircraft emissions are also radiatively active. The additional emissions include water vapour, NO<sub>x</sub>, soot and sulphates. Research on the climate impact of the non-CO<sub>2</sub> gases is ongoing and there is some uncertainty in current estimates (for further detail see Sausen et al., 2005). The apportionment regimes outlined here may also be suitable for some or all of the other emissions when their climate impacts are better understood. In the interim the non-CO<sub>2</sub> emissions impacts of potential mitigation options should also be considered.

<sup>1</sup> The term 'consumer' is used in this context to refer to those that use the aviation services provided by either domestic or international flights departing from the UK. Alternative terms for the 'consumer' that are used in existing inventories include 'final-user' or 'end-user'. For example, 'end-user' is used to describe how the emissions from electricity generation within the UK are apportioned to those that consume that electricity. The term 'consumer' is also used in relation to 'consumption based' emissions inventories to describe an allocation approach that allocates responsibility to the end-user for the lifecycle or embodied emissions in all goods and services no matter where they are physically released. This is not the meaning referred to here, we refer solely to methods by which emissions reported in compliance with UNFCCC are then allocated between regions.

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To deliver emission reductions from aviation, it is helpful to consider it as a complex system (after Randles, 2009), in which both consumers and producers play a role in the generation and thus the potential mitigation of emissions (Randles and Bows, 2009). In doing so, a wide range of points of intervention to reduce emissions can be identified, some of which are discussed in Section 2.1. The range and scope of emission reduction measures available suggest that a multi-level and multi-actor approach to emissions mitigation is beneficial. It is therefore important that opportunities to mitigate aviation emissions include those that can be taken at a regional level in coordination with action by UK, European and International bodies.

Many regional<sup>2</sup> authorities are taking up the challenge of climate change mitigation by producing their own emissions inventories and reduction strategies. Current inventories can be broadly categorised as: those that follow the emissions reporting standards of the United Nations Framework Convention on Climate Change (UNFCCC) which include emissions released within the UK geographical boundary reporting emissions from departing international flights as a separate memo item (see Intergovernmental Panel on Climate Change (IPCC), 2006); or inventories which are based on the emissions embodied within goods and services consumed by residents within the area of study, no matter where the emissions are geographically emitted (e.g. World Wildlife Fund UK (WWF-UK), 2006). This paper focuses on ways in which the CO<sub>2</sub> from the UK's aviation sector can be incorporated into the former type of inventory.

The following sections provide further information on the rationale behind this study and an assessment of different potential apportionment regimes suitable for aviation. Section 2 provides the background to the study: explaining why apportionment of aviation emissions to the regional level is useful; the potential measures that can be implemented to reduce CO<sub>2</sub> emissions and existing national and sub-national emissions allocation methods. Section 3 discusses the assessment criteria used to examine the different emission apportionment regimes presented and Section 4 describes and assesses each of the regimes in turn. Section 5 introduces a new hybrid apportionment regime and Section 6 provides recommendations for incorporating aviation emissions into regional inventories.

## 2. Background and rationale

Including aviation within regional inventories can assist regional decision makers in developing a baseline upon which to base their mitigation strategies. Furthermore, the apportionment method used can provide insight into the role of different parties (both consumers and producers) within the region. The inclusion of aviation emissions in an inventory also complies with the requirement of an emissions budget in which all sources must be included to assess the overall impact on the climate. In addition, their inclusion can enable a region to:

- Identify potential emission reduction options.
- Monitor the impact of aviation policies.
- Monitor the effects of wider policies on aviation emissions.
- Understand the proportion of UK aviation emissions that are the 'responsibility' of the region.
- Compare the quantity of aviation emissions with other emission sources.

- Understand the users of aviation, in order to protect key economic sectors and the regional economy as a whole from any future constraints on aviation.

Regional bodies are able to influence aviation emissions in conjunction with other actors through a range of mechanisms. These include the funding of low carbon initiatives, through their role in regional strategic planning and development and importantly as a facilitator between regional actors. The following section provides an overview of potential CO<sub>2</sub> reduction opportunities which could be supported at a regional level.

### 2.1. Opportunities for the reduction of CO<sub>2</sub> from aviation

Fuel consumption (and hence CO<sub>2</sub> emissions) is determined by the total energy necessary for the flight and the efficiency with which fuel is converted into useful energy. The fossil carbon intensity of the fuel, in conjunction with the fuel consumption, determines total CO<sub>2</sub> emissions. Factors affecting the total amount of energy required for a flight include: aerodynamics; aircraft weight; flight length and altitude; atmospheric conditions (tail winds, temperature, etc.) and the time spent at each stage of flight operation (Intergovernmental Panel on Climate Change (IPCC), 2006). Influencing each of these factors can reduce fuel burn and hence CO<sub>2</sub> emissions. Not all measures aimed at reducing CO<sub>2</sub> lead to a commensurate reduction in the radiative forcing associated with other emissions such as NO<sub>x</sub>, sulphates and water vapour (Williams, 2007). However, the main organisations and points of intervention capable of delivering a reduction in total radiative forcing from aviation are, in general, the same. Table 1 identifies key points of intervention which could lead to a reduction in fuel burn.

In addition to technical changes, consumer's aviation-related behavioural practises also have significant influence, and may similarly be subject to intervention. Examples include, limiting luggage, reducing the weight of flight facilities and reducing individuals' (and organisations') propensity to fly. While in technical and behavioural terms, the former interventions are relatively straight forward, the latter are significantly more politically challenging. Interventions to encourage a reduction in the numbers of flights taken by frequent flyers cannot be adequately addressed within the constraints of this paper. See Randles and Mander (2009) for expanded discussion of these issues.

Before a region considers whether and how to reduce aviation emissions it is helpful to gain an understanding of the share of the UK's aviation emissions for which it could be deemed responsible. The next section explores the challenges that determining this share presents and offers some insight into why, to date, aviation is not systematically included in sub-national emissions inventories.

### 2.2. Challenges in the apportionment of aviation emissions to regions

Estimating the fuel burn and hence CO<sub>2</sub> emissions from aviation in accordance with UNFCCC guidance is straight forward. However, emission reduction programmes must then apportion 'responsibility' for these emissions in order to reflect regional parties' relative contributions and provide insight into potential emission reduction measures. Aviation provides an international service and emissions are not bounded by national borders, this in part, has led to difficulties in reaching an agreement on how to allocate international aviation emissions to nations. The lack of international agreement is complicated further by the range of approaches used in sub-national

<sup>2</sup> By regional we refer to a sub-national area under the European standard classification system by which a UK region would be classified as NUTS1.

**Table 1**

Examples of the points of intervention for mitigating the climate impacts of aviation.

	Primary intervention point	Complementary intervention point	Main phase of flight affected
<b>Energy intensity<sup>a</sup></b>			
Aircraft aerodynamics	Aircraft manufacturers	Airlines/consumer acceptance	LTO+cruise
Type of aircraft	Aircraft manufacturers	Airlines/consumer acceptance	
Weight lifted	Aircraft manufacturers	Airlines-number of passengers and baggage and freight lifted	LTO+cruise
Time spent stacking	Local Air Traffic Control (ATC)	Airport management, government over new runways	LTO
Taxiing time	Airport management	Airlines	LTO
Descent time/engine use	Airport management, local ATC	Airlines	LTO
Route	Air traffic control	National governments	Cruise
Altitude	Air traffic control	Aircraft manufacturers	Cruise
Engine efficiency	Aircraft manufacturers	Airline demand/consumer preferences	LTO+cruise
Engine maintenance and age	Airlines	Manufacturers	LTO+cruise
Operating conditions	Air traffic control		LTO+cruise
<b>Fuel fossil CO<sub>2</sub> intensity</b>			
% Biofuel/Synfuel blend or alternative	Airlines	Fuel supply chain and aircraft manufacturers	LTO+cruise
<b>Consumer demand and emission intensity/passenger (illustrative)<sup>a</sup></b>			
Number of passengers	Pricing (compared to disposable income)	Improved alternative transport modes	LTO+cruise
Weight (baggage, in-flight services, freight, etc.)	Airline restrictions	Supply chain of in-flight services and freight containers	LTO+cruise
Popularity of different destinations	Marketing	Tourist infrastructure	Cruise only, or LTO+cruise

<sup>a</sup> Arguably the factors listed under these categories may be interchangeable.

inventories to allocate CO<sub>2</sub> emissions from the energy sector between regions. The current status of international allocation negotiations is outlined in Section 2.3, here we focus on national factors which influence emissions allocation.

National greenhouse gas inventory reporting follows the procedures and principles developed previously for air pollutant inventories. In an air pollutant emissions inventory, the responsibility for pollutants is allocated to the source or producer. This is done for two main reasons, firstly because the release location determines the impact on air quality, and secondly in order to identify and monitor pollution abatement opportunities. For air pollutants, abatement measures are mainly implemented by the pollutant producer or source. The allocation of CO<sub>2</sub> from fossil fuel combustion in sub-national greenhouse gas inventories does not always adhere to the source or producer-based principles of air pollutant inventories. The burning of fossil fuels releases CO<sub>2</sub> and H<sub>2</sub>O together with various air pollutants. Whereas air pollutants can be reduced at source using different abatement measures CO<sub>2</sub> release cannot currently be prevented. Furthermore, the impact of CO<sub>2</sub> on climate change is, in general, independent of the exact location of release.

The distinction between air pollutants and CO<sub>2</sub> must be taken into account when designing a CO<sub>2</sub> inventory to inform mitigation strategies for regions, simply following a traditional air pollutant inventory methodology, as has been done at the national level, may not be suitable. The only measure currently available to prevent the release of CO<sub>2</sub> from fossil fuel combustion is to switch to alternative energy sources. Decarbonising energy provision is challenging, and it is argued the burden should not fall solely on the producers. Allocating the CO<sub>2</sub> released from national energy production to the source in sub-national inventories is deemed to unfairly burden those areas hosting large sources such as coal fired power stations or oil refineries. Therefore, the emissions associated with the production, transformation and transport of energy are often attributed to the end-user of the energy, see for example this allocation method applied in the UK's Local Authority CO<sub>2</sub> statistics (DECC (Department for Energy and Climate Change), 2009). Action at a regional level is often then targeted at reducing energy demand rather than attempting to influence the fossil fuel use in national electricity generation.

Mirroring the consumer approach used by DECC (2009) would involve apportioning emissions to those that use the services provided by UK airports. Airports do not provide a service solely for residents in the local vicinity; they also serve residents and organisations from a much wider catchment area. For example, 60% of passengers terminating at Manchester Airport in 2006 started their journey from the English North West region in which it is situated; 19% started from the neighbouring region of Yorkshire and Humberside and 7% started from the West Midlands (CAA (Civil Aviation Authority), 2007). These passengers included both UK residents as well as international visitors on their return journey. Likewise, the direct economic benefit of the airport, airlines and associated services may not solely benefit the administrative area of the airport. The question therefore arises, should the emissions associated with the transport services provided at the airport be shared with other areas that fall under different administrative jurisdictions?

The challenges faced when apportioning emissions to the region mirror the challenges faced by those attempting to negotiate an international agreement to incorporate international aviation emission reduction targets into a post-Kyoto framework. The accepted international method determines the size of the UK's aviation emissions that must be shared between the regions and Devolved Administrations. A regional apportionment method must be compatible with the international method to ensure emissions are neither omitted nor double counted. The status of the negotiations to date is outlined below.

### 2.3. The treatment of aviation emissions in international agreements

At the time of the Kyoto negotiations, an accepted methodology of apportioning international aviation emissions between different countries was not available. Instead, Article 2.2 of the Kyoto Protocol asks Annex I countries to limit or reduce greenhouse gas emissions from international aviation through the International Civil Aviation Organization (ICAO). In addition, in 1995 the United Nations Framework Convention on Climate Change's (UNFCCC's) Subsidiary Body for Scientific and Technological Advice (SBSTA) was asked by the Conference of

**Table 2**  
International aviation and shipping allocation options proposed by the UNFCCC's SBSTA.

International aviation emissions allocation method	
<b>Option 1</b>	No allocation, as is the current situation (any emission reductions delivered by the whole sector)
<b>Option 2</b>	Allocation of global bunker sales (fuels sold for international flights) and associated emissions to parties in proportion to their national emissions
<b>Option 3</b>	Allocation to parties according to the country where the bunker fuel is sold
<b>Option 4</b>	Allocation to parties according to the nationality of the transporting company, or to the country where an aircraft is registered, or to the country of the operator
<b>Option 5</b>	(a) Allocation to parties according to the country of (i) departure or (ii) destination of an aircraft, alternatively (b), the emissions related to the journey of an aircraft could be shared by the country of departure and the country of arrival
<b>Option 6</b>	Allocation to parties according to the country of departure or destination of passenger or cargo. Alternatively, the emissions related to the journey of passengers or cargo could be shared by the country of departure and the country of arrival
<b>Option 7</b>	Allocation to parties according to the country of origin of passengers or owner of cargo
<b>Option 8</b>	Allocation to the party of all emissions generated in its national airspace

Parties (COP) 1 to explore the issue of allocation and control of emissions from the fuel used for international aviation (Den Elzen et al., 2007; UNFCCC, 1996a, b).

The methodologies proposed for the apportionment of international aviation emissions to countries by the UNFCCC's SBSTA are given in Table 2 (UNFCCC, 1996a, b). These methods are currently under discussion to enable aviations inclusion in a post-Kyoto agreement.

Current reporting requirements under the UNFCCC's Kyoto Protocol demand that each Annex 1 country includes international aviation emissions in its annual return as a separate 'memo' item. These figures are estimated in accordance with guidance from the Intergovernmental Panel on Climate Change (IPCC) based on Option 3 or 5ai above (Intergovernmental Panel on Climate Change (IPCC), 2006). It is important to note here that options 3 and 5 are 'producer' based allocation methods, a term to be expanded upon in Section 2.4. The UK's Committee on Climate Change has based their inclusion of international aviation for the country's long-term emission reduction target according to the amount of fuel sold in the UK for international flights—option 3. In doing so they note that the UK's allocation under options 4, 5 and 6 gives similar estimates to option 3, approximately 8% of global international aviation emissions in 1990 (CCC, 2008). This study has explored methods of dividing the aviation sector's emissions estimated using option 3 between regions, in doing so noting that option 3 strongly correlates to option 5ai, as bunker fuel sales primarily service departing international UK flights.

#### 2.4. CO<sub>2</sub> emissions accounting and allocation approaches used in existing regional inventories

At a regional level, several inventory methods commensurate with the UNFCCC have been developed (e.g. DECC, 2009; Carney, 2006), with each method tailored to a specific purpose and regional data availability. They can be distinguished by the method used to estimate the emissions from a sector—either 'top-down' or 'bottom-up' (Lindley et al., 1996; Lindley, 1998), and by their respective allocation approach used to apportion the

CO<sub>2</sub> emissions from an individual sector to either the producer of the emissions from that sector or to the consumer/end-user of the goods and services the sector provides (Bastianoni et al., 2004; Lenzen et al., 2007).<sup>3</sup> This categorisation can be used to frame possible aviation apportionment regimes.

##### 2.4.1. Emissions accounting approaches

The first categorisation is to differentiate between the two principal emissions accounting methods used in regional inventories. A top-down accounting method uses regional and national statistics to scale down UK total emissions for a sector to the region using the following formulae (Baldasano, 1998)

$$E_R = \frac{S_R}{S_N} \times E_N \quad (1)$$

where  $E_R$  is the regional emission;  $S_R$  the regional statistic (e.g. population);  $S_N$  the national statistic and  $E_N$  the national emission.

This method assumes there is a uniform distribution of emissions across the sector associated with the chosen scalar, and does not allow for regional variations in for example, energy efficiency. A bottom-up method uses local activity data such as tonnes of fuel consumed multiplied by an emission factor related to the carbon content of the fuel to estimate emissions using more detailed local information.

Most regional inventories use a combination of the two accounting methods (Baldasano, 1998). Furthermore, they often incorporate CO<sub>2</sub> sources using a mix of consumer- or producer-based allocation depending on the scale and purpose of the inventory. Whichever apportionment regime is used for the aviation sector, it should be compatible with the allocation approaches used to apportion emissions from other sectors in the wider inventory. The review of existing inventories in Section 2.5 describes the various apportionment regimes that have been applied to aviation to date.

#### 2.5. Aviation in existing regional CO<sub>2</sub> inventories

Several regions in the UK have their own climate change strategies and supporting regional greenhouse gas inventories (e.g. the North West and South East regions). Table 3 outlines a number of emissions inventories that have been developed for relevant sub-national administrative areas (regions, counties and an airport) and details how they have included aviation. For ease of emission calculation, and following the principles of air pollutant inventories, emissions are divided into those produced during the landing and take-off cycle (LTO) and those emitted at cruise altitude (cruise). The emissions are also split into those from domestic flights and those from international flights. The existing methods have been reviewed as part of this study, detail on the methods pursued further and their performance under our assessment criteria given in Section 3 can be found in Section 4.

### 3. Methodology Part 1—assessment criteria for the apportionment regimes

If an allocation method is to inform the delivery of an emissions mitigation strategy, it needs to be both coherent and transparent. In addition, where possible, it should help decision makers or other interested parties to understand the sensitivity of the emissions estimates to different intervention points and approaches. The criteria outlined below have been developed

<sup>3</sup> In practise emissions from various points along the chain of production may be allocated to the consumer (see Fawcett et al., 2002).



**Table 3**  
Existing sub-national inventories and their treatment of aviation emissions.

Inventory	Author	Treatment of aviation emissions	Approach
Greenhouse Gas Regional Inventory Project London Energy and CO <sub>2</sub> Emissions Inventory 2003	Carney (2006) Greater London Authority (GLA) (2007)	All LTO+domestic cruise. Emissions are allocated from total national aviation emissions based on the number of take-offs of aircraft from NW airports compared to the UK LTO only from Heathrow and London City Airports	Top-down producer Bottom-up-producer
Local Authority CO <sub>2</sub> Statistics 2005–2007 North west Emissions Inventory	AEA technology (DECC, 2009) AEA technology (Peace and McCubbin, 2009)	Aviation is not included Includes the taxiing and landing emissions of all flights arriving at airports in the North West	Bottom-up-producer
Local Authorities Carbon Counting Tool Norfolk Air Pollutant and Greenhouse Gas Inventory	South East Climate Change Partnership (SECCP) (2006) Wood (2007)	Aviation is not included LTO only both domestic and international	Bottom-up-producer
Manchester Airport	Upham et al. (2005)	LTO and cruise, domestic and international flight emissions included by ratio of passengers uplifted at Manchester airport per annum to the total uplifted in the UK	Top-down-consumer

from those used in SBSTA's international allocation proposals as examined by the IPCC (UNFCCC, 1996a, b).

- Could the required data be generated with sufficient precision and quality? Is this data publicly available and preferably free of charge?
- Is the method based on the “polluter pays” principle?
- Is the method consistent with the national inventory reported to the UNFCCC—could it be applied to all regions without overlap or omission?
- Is the allocation method analogous to the treatment of other sources within the regional inventory?
- Is the method capable of monitoring emissions in the long term and reflect mitigative action taken by the inventory user(s)?

Whilst (a), (c), (d) and (e) are self explanatory criteria (b) is worthy of further comment. The global nature and uncertainty of climate change impacts together with the technical difficulty for a polluter in abating fossil fuel related CO<sub>2</sub> emissions in comparison to other gaseous pollutants (see Section 2.2) renders ‘the polluter pays principle’ difficult to apply for CO<sub>2</sub> at national, and even more so, regional levels. At a regional level there are many organisations which play a role in ‘polluting’. Thus in place of this question, a more geographically specific issue would be to examine the relevant service providers (polluters) and consumers.

#### 4. Methodology Part 2—assessment of selected apportionment regimes

The aviation emission apportionment regimes were identified and developed from a literature review and expert elicitation through consultation with both regional inventory users and other inventory practitioners. The regimes developed are categorised in Table 4 in terms of the emissions accounting methodology and allocation principles adhered to. Inclusion of the method in Table 4 fulfils criteria (c) in terms of its compatibility with UNFCCC reporting and (d) for compatibility with the allocation approaches used for other sources in regional CO<sub>2</sub> inventories.

The paper now proceeds to assess these methods against the remaining criteria outlined in Section 3 and introduces an additional methodology in Section 5. The characteristics of each regime are summarised in Table 5.

**Table 4**  
Proposed aviation emissions apportionment regimes categorised by the method used to estimate the emissions and the allocation approach used.

Emissions allocation approach	Emissions accounting method	
	Top-down	Bottom-up
Producer	Scaled from national aviation emissions using regional statistics of: Economic information landing and take-off cycles	Fuel sold in region's airports Emissions from flights departing from a region's airport(s)
Consumer	Scaled from national aviation emissions using regional statistics of:  Regional airport's passenger and freight throughput Regional consumers' use of UK airports	Emissions associated with the departing UK flights taken by passengers starting their journey in the region and regional freight exporters

##### 4.1. Top-down producer

A top-down producer-based methodology allocates emissions to a region based on the ratio between a national and regional statistic relevant to the aviation sector. In applying the top-down producer allocation approach, there are a number of scaling factors appropriate for aviation. Two such factors from the literature relate to economic data and the use of landing and take-off data per airport in the region (Carney, 2006).

##### 4.1.1. Scaling using Gross Value Added (GVA) data

One of the main arguments by proponents of aviation expansion is that aviation provides a local economic benefit. When more detailed bottom-up data is not available the Greenhouse Regional Inventory Protocol (GRIP) scales down national emissions from a sector according to the economic activity of a particular industry in the region compared to the economic activity of that industry nationally (this approach is not used for aviation in GRIP) (Carney, 2006). The relationship is based on knowledge of the energy intensity of a particular industry and assumes that the emissions intensity from a sector is uniform across the country. The relationship between certain sectors of

**Table 5**

Summary of emission apportionment regime for aviation emission.

Apportionment regime	Allocation approach	Data requirements	Data reliability/availability	Advantages	Limitations
Scaling using GVA data	Top-down-producer	GVA of the airline industry in the regions	Available from ONS, based on survey data—medium reliability	Provides an allocation method related to the economic benefits brought to the regional economy by the producers of aviation emissions. Meets criteria (a), (c) and (d), partially fulfils (b)	Assumes emissions per unit of GVA are uniform across the airlines; not suitable for long-term monitoring. Fails criterion (e)
Scaling using number of LTO per airport in the region	Top-down-producer	Number of LTOs at UK airports split between domestic and international destinations	Available from CAA—high reliability	Easy to apply, as data is readily available. Meets criteria (a), (c) and (d), partially fulfils (b)	No distinction is made between European and longer-haul flight and the differences between their emissions. Fails criterion (e)
Scaling by regional airport throughput in tonnes lifted	Top-down-consumer	Passenger numbers and tonnes of freight and mail lifted by airport(s) in a region	Available from CAA—high reliability	Data is easy to obtain. Provides an insight into the service provided by the airports in the region and a proxy for economic benefit of their throughput to the airport. Meets criteria (a), (c) and (d), partially fulfils (b)	Does not distinguish between the origins of passengers using the airports—a region with a large airport will be penalised against one with a smaller airport. Fails criteria (b) and (e)
Scaling by the numbers of passenger starting their journey in the region that use UK airports	Top-down-consumer	Region of journey origin of passengers using each airport in the UK, plus freight-only flights departing from the region's airport(s)	Available for most airports—but not for all years from CAA; passenger origin based on gate surveys—medium reliability	Enables an assessment of the region's residents/visitors' use of airports. Meets criteria (d) and with the exception of freight fulfils (a), (b). Incorporating freight flights would meet criterion (c)	Assumes generic figures for emissions per passenger—does not take into account local variations in destination, aircraft used or local improvements in ATC failing criterion (e). Data on freight is not available to apply this approach consistently
Fuel sold at the region's airport(s)	Bottom-up-producer	Fuel sold at a regions airport(s)	High reliability if reported, but not publically available	Provides absolute fuel consumption and reliable estimate of CO <sub>2</sub> released as a result. Meets criteria (c) and (d) and partially fulfils (b) and (e)	Fuel sold at individual UK airports is not collected nationally. Fails criterion (a).
Emissions from flights departing from the region's airport(s)	Bottom-up-producer	Origin and destination for all flights using a region's airport(s), incl. plane and engine type	Flight data is available for a fee from CAA. Emissions modelling required	Data is available across regions. Can provide insights into the fuel efficiency of aircraft using airports and with sufficient detail potential savings from air traffic control measures can be modelled. Meets criteria (a), (c) and (d), partially fulfils criteria (b) and (e)	Depending on the level of flight detail obtained, fuel burn estimates may be subject to higher uncertainty. Does not completely fulfill criterion (b)
Emissions associated with the transport of passengers and freight that start their journey from the region	Bottom-up-consumer	Emissions from each departing flight taken by passengers or freight starting their journey from the region	Data not available	Represents the aviation emissions responsibility of the region's residents, visitors and freight exporters. Does not penalise a region for having an airport. Meets criteria (c) and (d) and partially (b) and (e)	The methodology to estimate passenger emissions per flight is available, however, the detailed passenger and freight data required is not available. Fails criterion (a)

the economy, their growth and emissions is well established and forms the basis for the UK's Environmental Accounts (Office for National Statistics (ONS), 2007).

Following this principle entails scaling national emissions to a region using the Gross Value Added (GVA) contribution of airlines. Airline GVA by region is chosen as airlines are the physical producer of CO<sub>2</sub>; emissions from an airport's activities are included elsewhere in an emissions inventory. The data required to apply this regime is available from the Annual Business Enquiry based on airlines registered in the Interdepartmental Business Register fulfilling criteria (a) (ONS, 2008). This method can also be replicated to other regions, fulfilling criterion (c), however, it should be noted that the airline GVA is based on survey data and the sum of the GVA reported for the UK's regions is approximately 6% lower than that reported for total GVA from airlines in the UK each year.

The GVA measure of economic benefit to a region does provide a reasonable metric for emission allocation, when considering the regional economic benefit attributed to a region's emissions producers. The disadvantage of this method is that it assumes that

emissions per unit of GVA are uniform across airlines, regardless of whether they are 'low cost' or 'legacy' operators. Airlines will differ in the routes they serve, the age of their fleet and the loading of their aircraft (see Miyoshi and Mason, 2009). Furthermore, local efficiency improvements could lead to a reduction in emissions while having a positive effect on airline GVA. Thus, assuming a direct GVA–emissions link would fail criterion (e) in this case.

A number of publications report wider economic benefits from aviation; however, these benefits are difficult to divide between the service providers and consumers (for example Oxford Economic Forecasting (OEF), 1999). A similarly economic 'top-down consumer' approach could be applied to allocate emissions based on the economic benefits brought to the region from the aviation services provided to the region's consumers. However, the necessary economic analysis is not consistently available between regions (failing criteria (a) and (c)) and many benefits cannot be measured using an economic metric. An alternative would be to use GVA from all sectors within the region as the scalar until more consistent and agreed methods of analysing

the economic impacts of aviation services in a region are available. This approach has the same limitations described for scaling by airline GVA above.

#### 4.1.2. Scaling using Landing and Take-off (LTO) information

Carney (2006) used the number of LTO's at regional airports compared to the UK total as a scalar for domestic aviation. Data on the number of international and domestic LTOs for each airport is available from the Civil Aviation Authority (CAA) and EUROSTAT meeting criteria (a) and (c) (CAA, 2009a; EUROSTAT, 2009). This regime would give a reasonable approximation for domestic aviation emissions per region, as the lengths of domestic flights in the UK are fairly similar when compared with international destinations. There is of course a large difference between emissions from flights to European destinations and those further afield, making this less suitable for the apportionment of international emissions. This regime captures changes in emissions due to changes in the destination and number of flights from a region, however, it is not detailed enough to capture local changes in, for example, aircraft efficiency, failing to adequately meet criterion (e).

#### 4.2. Top-down consumer

Regimes under this approach make use of regional and national statistics about aviation passengers and freight (consumers). Passenger information is routinely collected at most major airports in the UK by the CAA and through the International Passenger Survey (CAA, 2007; ONS, 2007). Survey information includes details on the passenger's residence and the location from which they have started their journey.

Information about freight other than its weight is not publically available, and this limits the analysis that can be carried out to ascertain a region's responsibility for air freight. At present the majority of freight is transported in the hold of passenger aircraft. Dedicated freight flights made up 2.8% of flights that departed from UK airports in 2005 and accounted for approx 3% of aviation emissions in the same year (Wood et al., 2009). In terms of weight lifted, assuming a passenger plus baggage weight of 100kg, freight and mail represented 10.6% of total weight lifted through UK airports in 2005 (EUROSTAT, 2009). As can be seen from the statistics presented, freight-only flights make up a small percentage of total flights. Until information on the origin of freight carried by aircraft is known, applying a detailed consumer-based approach presents difficulties but this should not prevent the principles of this approach being tested.

##### 4.2.1. Scaling by airport throughput

Upham et al. (2005) used passenger numbers by airport as a suitable metric for apportioning national aviation emissions to an individual airport. This method can be extended to include freight and mail carried by air from a region by summing the weight of passengers and freight uplifted through a region's airport(s). Total weight lifted by region can be estimated using the tonnes of freight and mail lifted and passenger numbers by airport from EUROSTAT assuming a weight per passenger plus baggage of 100 kg. This data is routinely recorded by airports and is readily and freely available with a high degree of accuracy, meeting criterion (a) (EUROSTAT, 2009; European Environment Agency (EEA), 2007). The methodology can be applied consistently across the regions. The total weight of passengers and of freight passing through the UK's airports is the sum of those reported by each airport and hence this method would not result in omission or overlap, fulfilling criterion (c).

Using this regime the responsibility for emissions is based on an indicator of the volume of services to consumers provided by a region's airport(s). The region's emissions burden from aviation is therefore a reflection of both the presence (or not) of an airport(s) in a region and its popularity. However, one disadvantage of this methodology is that the region from which the passengers (or freight) started their journey is not acknowledged in the apportionment. The region is thus given the responsibility of emissions for which its airport operators benefit; however, any social and economic benefits arising from the flights may be gained by a different region thus failing criterion (b). This method does not distinguish between the differences in the lengths of flights served by different airports or differences in airport management, loading or aircraft and engine type, giving limited insight into the impact of future local emission reduction measures, also failing criterion (e).

##### 4.2.2. Scaling by regional consumers

An extension of the above approach is to use information on the region from which passengers and freight departing from UK airports start their journey to scale the UK's emissions to a region. The CAA's passenger surveys report the region of journey origin of passengers departing from each airport in the UK. The survey is conducted annually at Gatwick, Heathrow and Manchester airports in the UK, with other smaller airports sampled in rotation approximately every five years, thus partially fulfilling criterion (a) (CAA, 2007). Freely available data on the CAA's website breaks down each airport's passenger numbers by the region from which they start their journey (CAA, 2009b). More detailed information including a breakdown of the passengers on individual routes, their nationality and UK post code is available for a fee. The freely available survey data does not distinguish between UK and non-UK residents. It can be argued however, that non-UK residents visiting the region either as tourists or business travellers will have brought some benefit (both socially and economically) to that region, therefore it is 'fair' that the region is given some responsibility for the emissions from their return flights, fulfilling criterion (b). As many regions actively encourage overseas visitors for tourism or investment purposes, this would suggest they are valued (e.g. North West Development Agency (NWD), 2008; Visit Britain, 2009). It should also be noted that following the national allocation system whereby the UK takes responsibility for outbound international flights, we are not given responsibility for the return journeys of UK residents coming back from overseas.

This method uses terminating passengers rather than including those in transit, as the journey origin of transit passengers is not collected (CAA, 2007). Instead, their origin is collected at the airport they begin their journey from (if it is within the UK), leading to potential discrepancies in the collection of data between international hubs, unless spoke airport passenger statistics are used in the analysis as well. Without such data, it is recommended that transit passengers' emissions are allocated to the hub airport's region.

Information on the regional origin of freight and mail is not collected, thus limiting the use of this regime. Until such information is collected, the emissions from freight-only flights should be allocated to the departing airport's region. This method has similar advantages to the airport throughput approach above. However, by adding detail on the passenger's region of journey origin it attempts to relate aviation emission's to the region that benefits from the services provided to its residents and visitors. In addition, by scaling only the emissions from outbound flights, it is

compatible with aviation's emission total in the current UK inventory and therefore criterion (c).

#### 4.3. Bottom-up producer

Under this suite of apportionment regimes, the 'producer' is the airline. The emissions from a flight can be estimated using a number of different aviation models, each of which attempts to estimate the fuel burn and hence CO<sub>2</sub> emissions from a flight.

##### 4.3.1. Regional aviation fuels sales

The IPCC methodology has a tiered approach to estimating aviation emissions on a producer basis. Tier 1 is the simplest method, as it involves reporting the amount of aviation fuel sold in a country, and follows the SBSTA Option 3 approach (split between sales for domestic flights and international flights for Kyoto reporting requirements). This method can also be used for regions that host airports. It assumes firstly that fuel is sold for all flights departing that airport and that tankering, the practise by which airlines fill their aircraft with more fuel than the immediate flight requires, does not occur. However, the data required to apply this method is not collected hence failing criterion (a) (UK Government Department for Business, Enterprise and Regulatory Reform, pers. comm.).

##### 4.3.2. Emissions from regional outbound flights

Fuel use may also be estimated using information on the flights departing from an airport. Such an apportionment regime follows the Tier 3 IPCC national reporting requirements and is equivalent to SBSTA Option 5ai (Table 2). The region would be allocated the responsibility for the CO<sub>2</sub> from all flights departing from its airports, irrespective of whether the airport serves a wider catchment area than the administrative boundary in which it lies, thus while providing information on potential emission reductions over time, and meeting in part, criterion (e), it does not however, fully meet criterion (b). A methodology to estimate CO<sub>2</sub> emissions from flights is given in the European Emissions Inventory Guidebook and the information on the outbound flights needed to follow this methodology can be obtained from the CAA (EEA, 2007; CAA, 2008).

#### 4.4. Bottom-up-consumer

Bottom-up approaches are generally far more data intensive than their top-down equivalents. For a 'bottom-up consumer' regime, a high level of detailed information would be required, including the travel patterns of a regions' residents, visitors and freight exporters on domestic and departing international flights, as well as the emissions associated with their journeys. There are a number of commercial emissions models that have been produced to enable a passenger to estimate their personal carbon emissions from a flight by entering their flight number (e.g. Greenstone Carbon Management, 2008; Filippone, 2008). The use of such models is limited at a regional level, as such detailed information on the flights taken by all air passengers and all freight that starts their journey from the region is not publically available (failing to fulfill criterion (a)). Furthermore, the models do not provide sufficient information on the assumptions they make about freight carried in the hold of passenger flights to enable a consistent assessment incorporating freight to be carried out following this regime failing criterion (c).

Table 5 provides a summary of the different methods, their main advantages and disadvantages. From Table 5 and the discussion in Section 4 we demonstrate that no single apportionment regime adequately fulfils all the assessment criteria to

provide sufficient insight into the system for a regional administrator, although a combination of the regimes may do so. In the present political system, where single metrics or indicators are preferred, suggesting the use of a number of different regimes is not practical. Furthermore, the study from which the paper has arisen benefited from a steering group comprising of key inventory users in a UK region, including the Government Office, Regional Development Agency, Regional Assembly, and aviation industry advisors. Following a presentation of the above regimes to the steering group a desire was expressed for an approach that could reflect both producer- and consumer-based responsibility. As a consequence, a further methodology is developed in the next section in an attempt to provide a regime which better fulfils the assessment criteria, and responds to inventory user's requests.

### 5. Hybrid consumer-producer (HC-P) regime

A further apportionment regime is proposed here in an attempt to reflect the responsibilities of the region, through its role as a 'producer' of emissions and also as a service 'consumer'. While 'producers' are able to control the emissions intensity of the service they provide, 'consumers' are able to control the amount and type of services they use. By sharing the responsibility between producers and consumers the regime can provide an insight into both actors in the region and can respond to emission reduction measures targeted at both. A theoretical justification for sharing the responsibility for emissions between a producer and consumer is given in Lenzen et al. (2007).

The hybrid regime outlined below has been presented back to the original steering group and also to a wide range of inventory users and compilers, including academics, policy makers and consultants for feedback at workshops and presentations. The proposed method has been well received as a useful contribution to understanding aviation emissions attributable to the regions by inventory users. However, the regime has faced criticism for being more complicated compared to a producer-based method. For any regime to be adopted it must be politically acceptable as well as academically justifiable, the purely producer-based approach was not acceptable to the inventory users who provided feedback.

The regime proposed is to apportion the emissions from the take-off and landing cycle (LTO) of aircraft using airports within the inventory region to that region and to apportion the emissions from the cruise section of all departing UK passenger flights to the region according to the proportion of passengers that start their journey from that region. The full assessment of the regime against the criteria is given in Table 6. This method has been developed to reflect firstly, the potential influence on aviation emissions that a region can have and secondly, to allocate responsibility according to the regional beneficiaries of aviation reflecting both the direct economic impact of an airport and the benefits of the services aviation provides to users within the region and therefore fulfilling criterion (b). Once again, without information on the origin of freight lifted from UK airports, applying a consistent 'consumer' approach for freight transport is not possible. Instead, in order to ensure consistency with the national emissions total for aviation, emissions from freight-only flights could be allocated to the region of origin until further data is routinely collected. As discussed in Section 4.2, freight-only flights account for a small fraction of total aviation emissions and as the primary purpose of a passenger flight is to transport people, emissions from these flights are for now allocated solely according to the passenger origin.

Data on the LTO cycles from airports is regularly collected for air quality assessments. The emissions and influencing factors associated with each part of the cycle are well understood.



**Table 6**  
Assessment of the hybrid C–P regime against assessment criteria.

Criterion	Hybrid regime performance
Could the required data be generated with sufficient precision and quality? Is this data publicly available and preferably free of charge?	Yes, UK flight data (including data on freight and passenger numbers) can be obtained from the CAA for a small charge. Passenger survey data detailing passengers' journey origin, nationality and flight destination is available from the CAA and the ONS. When detailed freight data is available this can be easily incorporated
Does the method reflect the region's service providers and consumers?	Yes, the LTO emissions reflect the region's role as a provider of aviation services, the apportioned share of UK cruise emissions according to passengers residing in or visiting a region reflects the wider benefits the region receives from aviation
Is the method consistent with the national inventory reported to the UNFCCC—could it be applied to all regions without overlap or omission?	Yes, by only apportioning domestic flights and departing international flights the approach enables each region and UK Devolved Administration to be allocated a share of the total UK aviation emissions as submitted to the UNFCCC
Is the allocation method analogous to the treatment of other sources within the regional inventory?	Yes, sharing emissions between the producer and consumer using this regime is similar to that used in some inventories for allocating the CO <sub>2</sub> from electricity generation where the CO <sub>2</sub> associated solely with electricity production is allocated to the consumer and onsite power station energy use and transmission losses are allocated to the producer
Is the method capable of monitoring emissions in the long term and reflect mitigative action taken by the inventory user(s)?	Yes, local action to reduce emissions from the LTO cycle can be monitored using this method. In addition changes in the travel patterns of a region's residents and visitors and efficiency improvements in the industry as a whole can be monitored

Including the CO<sub>2</sub> from the LTO into an inventory can enable a greater understanding of how emission reduction methods from ground movements around the airport and changes in air traffic control practises can be used to reduce emissions from this cycle fulfilling criteria (a) and (e). Furthermore, the 'optimisation step' of the European airport carbon accreditation scheme incorporates the LTO cycle emissions into an airport's carbon footprint and provides guidance on how these emissions can be reduced through cooperation with third parties (Airport Carbon Accreditation (ACI), 2009). The LTO emissions are also linked to the direct economic benefits accrued from the number of flights departing from an airport. The number of flights is proportional to the number of passengers or tonnes of freight lifted and the associated direct economic benefits of local airport and airline services.

Dividing the emissions from the cruise section of departing UK flights between the regions according to the proportion of passengers (both residents and visitors) that begin their journey in each region, gives an indication of how frequently people residing in the region fly, and the number of visitors to the region that travel by air. The information needed to apply this regime is collected through passenger surveys organised by the CAA and ONS, as described in Section 4.2 (CAA, 2007; ONS, 2007). This

regime acknowledges the wider catchment area of airports, by dividing up the cruise emissions between regions, those without an international airport would share the emissions burden corresponding to their resident's propensity to fly and the visitors the region attracts that travel by air, fulfilling criteria (b) and (e).

In addition, this method enables a region to consider how it can intervene to reduce emissions from this sector (if desired). Firstly, LTO emissions can be addressed through negotiations with airports, local spatial planners, airlines, national air traffic control and national government for example through the airport carbon accreditation scheme (Airport Carbon Accreditation (ACI), 2009). Secondly, the cruise emissions can be reduced through efficiency improvements as well as measures to slow the growth in demand for air travel. Although growth in demand for aviation has slowed in recent years, in part, due to the economic down turn, analysis by the CAA suggests that this slow down is likely to be short lived and growth rates are expected to recover in the longer term (CAA, 2008). Action to reduce growth rates is particularly contentious, although until improvements in technology are able match this growth in demand, it is likely to be necessary to meet Government emission (and temperature) targets. Here, regions and other sub-national administrations can play a role, for example, in promoting local tourism.

## 6. Conclusions

Having considered the current array of apportionment regimes, the authors suggest a new hybrid C–P approach. The hybrid approach brings together the principal virtues of the producer and consumer allocation approaches in a form applicable to regional inventories that comply with UNFCCC reporting guidelines. It provides insights into the potential for emission reductions from both the LTO and cruise phases of flights that a region could influence and monitor. The method uses available and regularly collected data. Moreover, when compared with the alternative apportionment regimes discussed within the paper, the regime offers an arguably more equitable apportionment of emissions by sharing the responsibility between producers and consumers in a manner compatible with the treatment of CO<sub>2</sub> from other energy sectors in existing sub-national inventories (see DECC, 2009). As a consequence this method reflects those that produce aviation emissions within the region and the benefit that the region receives from services that the UK aviation sector provides.

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