In 2008, the UK Committee on Climate Change (CCC) published their first climate change strategy for the UK setting out a pathway by which the UK could deliver a cumulative emission reduction target. At the time, the role of aviation in this was undetermined, awaiting a Government decision on whether or how international aviation should be included in the targets [1]. In January 2009, the Government clarified its position and set a target that aviation emissions of CO₂ in 2050 should not exceed 2005 levels, asking that the CCC provide advice as to how this target could be reached [2]. The CCC subsequent advice, published December 2009, is based on their assessment of possible passenger demand projections with and without capacity and carbon price constraints coupled with a number of technological scenarios for delivering CO₂ savings. Following their analysis of the most likely technological development pathway for global aviation, the CCC recommended that future UK aviation policies be compatible with a maximum increase in air traffic movements of approximately 55% between 2005 and 2050, and a maximum of a 60% increase in passenger demand for the same timescale. Despite a recent downturn in air transport following economic events, the CCC and the UK’s Civil Aviation Authority (CAA) expect growth in demand to resume as GDP returns to growth, projecting a passenger growth rate of 115% from 2005 to 2050, taking into account a future carbon price and capacity constraints. This leaves a significant challenge for policy makers [2,3].

More recently, the Government has announced a hiatus on new runways at Heathrow and Stansted, with the expectation that any new capacity will be met by regional airports [101]. Despite setting the UK’s target at the national level, the reality of emission mitigation policy is that much of the practical implementation requires either delivery of emission reductions from this sector.

International agreement has not been reached on how to divide the responsibility for the emissions produced from international aviation to individual countries. This in turn has led to difficulties in attributing all aviation emissions to sub-national inventories. To achieve CO₂ equivalent stabilization targets, all sources of emissions must be taken into account. A relatively minor source today may grow to become a major contributor in the future. Sub-national administrations are key to the delivery of emissions reduction; therefore, the inclusion of aviation within their baseline is important to ensure reductions are commensurate with the avoidance of dangerous climate change. This article quantifies CO₂ emissions from aviation that could be attributed to the UK Devolved Administrations and Regions, using the current standard methodology and a range of alternative apportionment methods. The background and rationale to the apportionment methods chosen are published elsewhere. Here, the focus is on the application of the selected methods to allocate aviation emissions to sub-national administrations in order to compare the geographic distribution of aviation emissions across Great Britain when using different approaches. The results demonstrate the impact that the location of an airport makes to its region’s aviation emissions profile and the distribution of aviation users in Great Britain, providing an indication of how different regions and devolved administrations could most appropriately support the delivery of emission reductions from this sector.

Aviation development & emission reductions at the regional & local level

Existing aviation planning policy outlined in the Aviation White Paper has been described as a growth facilitator, creating a ‘self perpetuating cycle’ of demand prediction, capacity expansion and induced growth [8,9]. Regional and devolved administrations together with local public and private organizations have a demonstrable role in this cycle [9]. Growth in aviation in the regions is supported through a number of mechanisms including the Route Development Fund (RDF), strategies to encourage in-bound tourism and business links and the support of airport master plans (AMPs) in regional spatial strategies and local development frameworks. The following section outlines these mechanisms and how they contribute to the development of aviation and in turn how they can be used to reduce GHG emissions from the sector. Finally, the wider importance of considering aviation in sub-national climate change strategies is discussed.

The RDF was a scheme in which Devolved Administrations and Regional Development Agencies could offer start-up aid for a limited period for new routes from airports in their areas [102]. It was predominantly used to promote new direct international flights between regional airports and destinations of strategic importance for business development or in-bound tourism; for example, routes between Edinburgh and Atlanta and Munich were supported via this mechanism by the Scottish Government [103]. The use of the RDF is often accompanied with economic and tourism strategies aimed at marketing the region overseas to create a market for a new route, as well as promoting the international connectivity of the region in general [10,104].

The 2007 Aviation White Paper outlines the Government’s principle policies on the increase of regional airport capacity and expects airports to develop AMPs outlining how they expect to respond to the conclusions of the white paper. The AMPs include plans for development, including details of significant planning applications that they expect to submit in the near term. Working with the relevant local authority the plans are to be integrated into the local authority’s local development framework (LDF) as an area action plan. The LDF in turn informs the regional spatial strategy. This mechanism provides both Local Authorities and regions with a demonstrable role in supporting the delivery of an AMP.

Many local authorities in the UK also have a direct interest in the operations and expansion of their local airport(s); for example, Greater Manchester authorities entirely own the Manchester Airport Group PLC, which operates four regional airports. Similarly, a number of other UK regional airports are at least partially owned by their local authority [11,12]. This would indicate that there is a direct opportunity for the public sector to address this source of emissions. For other areas of the UK there are alternative mechanisms that could be drawn upon to facilitate decarbonization, including the Strategic Aviation Special Interest Group of the Local Government Association (SASIG); the UK’s dedicated organization to deliver national aviation strategies into regional strategies and other local planning. Within its core objectives it lists:

“To promote the need for long-term, sustainable aviation policies that lead to a reduction in the environmental impact of aviation whilst securing appropriate social and economic benefits to identify. To promote the changes needed to move towards sustainable aviation practices within the industry and Government” [105].

Just as regional and local government have a supporting role in the development of aviation in the UK, with the cooperation of other actors they are also able to influence the reduction of emissions from this sector. Whilst aviation is commonly regarded as an industry, which responds to broader political and economic drivers, the mechanisms outlined above demonstrate efforts that attempt to shape these to locally defined objectives. Such coordination arrangements including diverse non-public sector institutions designed to deliver specific tasks can be classified as type II multi-level governance [13]. A form of governance that has been
Rationale for this article

Identified with sub-national climate change activity [14]. In the case of aviation these institutions would include airport operators, airlines, user groups, NGOs as well as public bodies. Mechanisms additional to those above, that can be used to tackle aviation emissions, would include the UK’s Local Strategic Partnerships (LSP); a recognized route of bringing together such institutions to work towards community goals. Many LSPs already coordinate action on climate change across the public, private and not-for profit sectors [106].

Further to the role of regional and local actors in the development of aviation services and thus supporting the delivery of emission reductions, the role of the sector’s emissions within a wider climate mitigation strategy is also important to acknowledge. In setting carbon constraints for industry and aviation within the same GHG budget, as in the case of the UK Climate Change Act 2008, the relative success of emission reduction in each sector has secondary impacts on the budget remaining for others, which may or may not be experienced as a carbon price. Consequently, development plans that are founded upon growth in carbon intensive industries must be cognizant of the emissions trajectory of others such as aviation. Similarly, development plans reliant on economic linkages between aviation services and other economic sectors must recognize the implications of these constraints [15]. Possessing an understanding of the emissions responsibility of different sources within the administrative boundary is therefore important. Beyond the proactive management of aviation emissions within a wider decarbonization strategy, emissions information can therefore also be used to anticipate the future impacts of emission constraints on not only aviation but other associated and dependent economic activities.

Methodology

A set of four emission allocation regimes are used to apportion CO₂ from domestic and international aviation emissions to the English regions, Wales and Scotland. The rationale behind each regime is described in Wood et al. whereas here, more detailed emission calculations are presented for GB [22]. The apportionment focuses on CO₂ to demonstrate the principles of the regimes. It is also appropriate for use with both CH₄ and N₂O; however, the impact of these emissions from this source on the climate are small in comparison with CO₂.

The apportionment regimes are derived from one or both of the two principal methods of allocating responsibility for emissions: the producer-based and consumer-based methods. In the former, emissions are allocated to the producer, which in this case is interpreted as flights departing from an airport in a given region or devolved administration; by contrast, the consumer-focused method allocates emissions to the end-user (i.e., the passenger [the passenger is focused on as the consumer in this article. At present, data on the origin and destination of freight that is carried on both passenger and freight only aircraft is not published. A meaningful method of allocating the emissions of freight transport to the ‘consumer’ is not yet available. Further work could develop this. In the interim, as demonstrated by the results below, since emissions from freight only flights represent a small proportion of total aviation emissions and freight is of a secondary purpose when carried on passenger flights, we focus
on the passenger as the consumer. The method also excludes non-commercial flights such as military, police and test flights; such emissions are not readily estimated since much of the air traffic data on such flights is not publicly available.

As such, this is consistent with the principles underpinning existing national and regional emissions inventories [107]. Apportioning emissions to the producer rather than the end-user, or vice-versa, provides different messages on what the focus of emission mitigation measures should be. The choice of method depends on a range of factors, including ease of data gathering, data uncertainty or the most useful from a mitigation policy perspective. It is possible to use a combination of methods to inform different aspects of mitigation policy. To reflect this, a number of apportionment methods are assessed and their potential use in an emissions mitigation strategy is examined.

Currently, the emissions from domestic flights are included in the UK’s emission reduction targets under the Kyoto Protocol, with additional reporting requirements demanding each Annex 1 country include international emissions (for both aviation and shipping) in its annual return as a separate ‘memo’ item. Therefore, emissions from both departing international flights as well as domestic flights are included in the UK’s annual GHG returns and at present are within the scope of the emissions included in the UK Government targets. These figures are estimated in accordance with guidance from the Intergovernmental Panel on Climate Change (IPCC) [23]. The UK follows the IPCC’s tier 3 methodology, whereby the emissions from domestic flights and departing international flights are estimated using information on the aircraft type and flight destination. The application of this method in the UK is reported by Watterson et al. [24]; the methodology has been followed in this paper to comply with current government estimates and accounting standards using data purchased from the CAA on all flight movements from UK airports. The resulting estimates form the basis for the application of each regime and each is thus consistent with the scope of aviation emissions subject to current UK Government targets [2].

The year 2005 has been chosen for analysis since it is both the baseline year used by the CCC and provides the target level of emissions that the sector is expected to stabilize at by 2050 [2]. The results are given for total aviation emissions both domestic and international. This data is available from the author for regime 1. The passenger survey data used in regimes 3 and 4 combined both domestic and international passengers; the cost of purchasing more detailed data was prohibitive.

**Regime 1. Producer-based: emissions from outbound domestic & international flights from the region’s airports.**

This method of apportionment is currently used in official reports on the aviation emissions for the UK’s devolved administrations [25]. The method is applied to all aircraft taking off from UK airports reported to the CAA; however, supporting passenger data is only available for GB, therefore this is the only regime that includes the whole of the UK – this is discussed further in Section 3.

The emissions from a flight can be divided into two sections in order to estimate emissions. First, the emissions arising during the landing and take-off (LTO) cycle of a flight and second, the emissions released while the aircraft is at cruise altitude (defined as above 3000 ft or 1000 m [23]). The fuel burn and hence emissions associated with the LTO cycle, use of auxiliary power units (APUs) and cruise from flights departing from each UK airport in 2005 was estimated using the methodology described below, based on Watterson et al. [24]. The emissions are then apportioned to the region or devolved administration from which the flight departed. The total emissions estimated here have also been used to underpin the apportionment methods for the remaining three regimes.

**Emissions from the LTO Cycle**

Emissions from the LTO cycle are estimated following the methodology given by Watterson et al. [24] using data provided by the CAA [108]. The CAA provided information by airport for every departing domestic and international flight including aircraft type, destination and great circle distance for both passenger and freight only flights during 2005. The data includes all commercial civilian aircraft movements within the UK, excluding general private light aircraft, official and demonstration flights.

The aircraft types provided by the CAA were matched to aircraft categories together with their corresponding engine type and fuel consumption rates at different thrust settings were taken from Watterson et al. [24]. The landing and take-off cycle can be broken down into eight phases: taxi out to the runway, hold, take-off roll, initial climb, climb out to 1000m, approach from 1000m, landing roll and taxi in. Watterson et al. provide thrust settings for each phase of the cycle in addition to the fuel consumption rate by aircraft type and either data or a methodology for estimating the length of time an aircraft spends in each stage of the LTO cycle according to the airport type [24]. For example, hold times were provided for Heathrow, Gatwick and Stansted; hold times at other airports were estimated depending on the number of air transport movements at that airport per
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annual following guidance from Watterson et al. [24]. Equation 1 describes the method used to estimate fuel consumption during the LTO using the time each aircraft spends at different thrust settings.

\[ F_s = N_i \sum T_{s,t,a} \]  
Equation 1

where \( F_s \) is fuel consumption over the landing and take-off cycle for aircraft type \( s \) at airport type \( a \); \( N \) is the number of engines on an aircraft type \( s \); \( T_{s,t,a} \) is time spent at thrust setting \( t \) for each airport type \( a \), calculated from the times each aircraft spends during each section of the LTO cycle (i.e., approach, landing roll, take-off roll and initial climb, climb out, taxi in and out and hold) for each airport type or in the case of taxi and hold times for each airport; \( f_{s,a,t} \) is the weighted average fuel flow for an engine on aircraft type \( s \) at airport type \( a \) for thrust setting \( t \); \( a \) is the airport type, either Heathrow, Gatwick, Stansted, regional or small; \( s \) is the specific aircraft type; and \( t \) is the thrust setting of aircraft engine (dependent on the stage of the LTO and airport type).

In addition to fuel consumed during the LTO cycle, fuel combustion from auxiliary power units (APUs; on board generators to provide energy to the aircraft while the main engines are idle) was estimated, also following Watterson et al. [24]. The total aviation turbine fuel burn was multiplied by an emission factor of 3.15 kgCO₂/kgfuel¹ and aviation spirit fuel burn (from a small number of light aircraft reported by the CAA) by 3.128 kgCO₂/kgfuel¹ [26]. Emissions from APUs have been included in the LTO estimates for apportionment purposes.

Cruise emissions
Cruise emissions were estimated by using aircraft specific fuel consumption rates for the distance flown. The Great Circle Distance provided by the CAA was multiplied by a factor of 9.5% to take into account deviations from this route following Watterson et al. [24] and multiplied by the appropriate fuel consumption factor to estimate fuel burn during cruise.

- **Regime 2. Downscaling by population: an equal per capita distribution of total aviation emissions**

The second apportionment option provides the first comparison, scaling total aviation emissions from airports in GB to each region assuming an equal per capita distribution using sub-national population statistics for 2005 from the Office of National Statistics [109]. To apply this regime, GB's total aviation emissions are multiplied by the percentage of the total GB population that reside in that region/devolved administration (DA). Downscaling by population is often the default methodology used for sub-national inventories for sectors where insufficient data exists at the local level; here, it has an additional interest, providing an indicator of the spatial distribution of aviation emissions if all residents consumed the same amount of aviation services and can be used for comparison with consumption patterns indicated in regime 3.

- **Regime 3. Consumer-based: scaling by the proportion of passengers traveling from each airport whose journey originates in a region or devolved administration.**

This method uses data from the CAA’s Departing Passenger Surveys [27–30] to derive a scalar to divide the emissions from the flights of each GB airport to the regions from which their passengers start their journey. The survey gives a split by airport of the origin of passengers who are on its departing flights. For UK residents, this is the region or devolved administration that they start their journey from; for example, their home, and for overseas visitors the region/DA that they have traveled from to make the journey (e.g., a hotel where they have stayed on holiday). When ascertaining the journey origin, stop-overs at airport hotels or other places stopped at specifically for traveling to the airport are not included in the definition of journey origin. Therefore, overseas visitors origins will be defined as the region/DA they have last visited as part of their trip. The proportion of passengers at each of the surveyed airports who start their journey from each of the regions and DAs, is used to disaggregate the emissions from each airport and apportion them to the passenger’s region of origin described in Equation 2.

\[ R = \sum (A_i \times P_{ej}) \]  
Equation 2

where \( R \) is a region or DAs attributed emissions; \( A_i \) is the total emissions from departing flights from airport \( J \); \( P_{ej} \) is the proportion of terminal passengers who started their journey from region/DA \( R \) using airport \( J \).

By using this data source, a number of assumptions are made, including: first, that the survey is representative of all passengers (as it is designed to be) and that the mix of flight destinations taken by passengers from an airport is consistent for both scheduled and chartered flights for passengers in each area; for example, that north west residents and visitors travel to the same destinations from Newcastle airport as passengers from Scotland who fly from Newcastle. Information is collected on the origin of passengers by flight destination for each airport; however, the data are too costly to obtain for this study. This is a limitation of the method, and should be taken into account when using the results. A passenger’s choice of airport is likely to be determined by both proximity to the airport and also
the destination and price of flights available from that airport. Further work could look at this in greater detail; intuitively one could expect flight destinations to mirror the economic affluence of a region compared with another in addition to the geographical differences that influence the use of domestic flights. For example, one could expect Scottish residents to take more domestic flights than those in London, owing to the geographical location and the numerous small islands off the Scottish coast; attributing a general distribution of flight destination to Scotland could overestimate their ‘end-user’ emissions allocation.

The Departing Passenger Survey is carried out annually on passengers departing from UK airports and collects among other things information on their journey origin (within the UK), ultimate destination and purpose of travel. The survey is taken of passengers departing flights at the gate-room; a stratified sample of passengers on both scheduled and charter flights is taken to cover a sample population of both flight numbers and routes from the survey airport during the year. The survey covers all terminal passengers – all landside passengers – both passengers arriving at the airport by surface transport to take a flight and those arriving by air who change flights at the airport onto a different aircraft. The latter passengers are termed interlining. The survey does omit transit passengers, those who arrive and depart on the same aircraft therefore not passing the survey point [110]. The numbers of both transit and terminal passengers are reported at each airport by the CAA. Terminal passenger origins are used as a scalar to redistribute aviation emissions to the region. For the purpose of emissions allocation, ‘transit’ passenger numbers have been attributed to the region of the airport; the proportion of transit passengers compared with terminal passengers varies between airport – for example, 0.3% at Heathrow, 1.4% at Manchester the UK’s main hub airports and 33% at Wick, an airport often used as a stopover on the way to other islands off the coast of Scotland.

The origin of the passenger is the region or country from which they started their journey to the airport (excluding any transitory stop offs en route). In practice this would generally entail a region being attributed the flights taken by its residents and other overseas visitors who have spent the time prior to their departure in the region. This does not take into consideration the fact that many overseas visitors to the UK may have traveled to a number of regions during their stay; however, the data required on overseas visitors (also collected by the CAA) to examine the ramifications of this was beyond the budget of this study. It would be an interesting future development to assess the potential impact of this on the emissions attributed to a region. Of the airports surveyed in 2005, 25.9% of terminating passengers were from overseas [28].

The airports surveyed annually are London, Heathrow, Stansted, Gatwick and Manchester; other regional airports are surveyed in rotation. In 2005 the Departing Passenger Survey was also carried out at London Luton, Aberdeen, Prestwick, Bournemouth, Durham Tees Valley, Edinburgh, Glasgow, Inverness, Leeds Bradford and Newcastle [28]. Additional survey data from other years was used to supplement the 2005 surveys; 2003, covering Birmingham, Bristol, Cardiff, Exeter, Liverpool and London City [27]; 2006, covering Nottingham East Midlands and charter passengers from Heathrow (this data was missing from the 2005 survey) [29] and 2007/2008, for Doncaster and Humberside Airports [30]. The airports covered by the four surveys carried over 97% of GB terminal passengers and, as such, they were considered to be a sufficient representation to use as a scalar. Survey data from years other than 2005 are used, noting that patterns may change year to year depending on routes and prices offered; however, there is no suitable alternative data source available.

The data does not include passengers traveling through airports in GB who cite their journey origin as Northern Ireland owing to the small fraction this represents. Similarly, passenger surveys of Northern Irish airports only report passengers as originating from either Northern or Southern Ireland. Similar information on Southern Irish airports is not available to apply this method fairly at present. The airports of the Isle of Man and the Channel Islands are not surveyed (nor are a number of very small UK airports e.g., Bara), it is assumed here that all passengers traveling from these airports originate from these islands, since individuals from the rest of the UK are unlikely to travel overland (or sea) to them for the sole purpose of flying on elsewhere. Passengers from the Channel Islands are included in the survey; however, the fraction of Guernsey and Jersey residents traveling from UK mainland airports is insignificant and was only picked up in the surveys at Gatwick as 0.05% of terminal passengers in 2005 [28].

Passenger flights also carry freight, attributing emissions to the ‘end-user’ of freight is fraught with both methodological and data availability difficulties [31]. Thus, the freight contained in passenger flights is not incorporated in this approach, with the rationale that the passenger is the primary purpose for these flights. The emissions associated with freight only flights are attributed to the airport’s region; these emissions represented 2.8% of total UK aviation emissions in 2005. It can be argued that a region benefits economically
from the associated services freight transport provides and therefore its emissions allocation should reflect this benefit.

- **Regime 4. Hybrid producer–consumer (end-user)**
  The final regime encompasses the principles behind both regimes 1 and 3. The hybrid regime allocates emissions from both international and domestic flights to a region based on:
  - The emissions from the LTO of all passenger flights departing from the relevant region.
  - The emissions from the LTO, plus cruise of all freight and mail only flights departing from airports in the relevant region.
  - The emissions from the cruise section of all flights departing from GB airports that can be attributed to terminating passengers who originate (either as residents or visitors) from the region of question.

For example, for passengers who start their journey in Wales but fly from Heathrow, an equivalent proportion of cruise emissions from flights departing from Heathrow will be allocated to Wales; however, the LTO emissions will be apportioned to Greater London. The rationale behind this method was developed in Wood *et al.* [22] and it is intended to reflect; first, the potential influence on aviation emissions that the region can have; and second, to allocate responsibility according to the regional beneficiaries of aviation, reflecting in part both the direct economic benefit of an airport and the benefits of the services that aviation provides to users within the region.

Emissions from the LTO and cruise section of UK flights were estimated using the methodology described in regime 1. The main step is to redistribute cruise emissions to the regions according to passenger origin. These emissions were allocated to the English regions and DAs using information on the split of departing passenger origin between the regions and DAs for each of the main UK airports reported by the CAA’s Passenger Surveys as in regime 3 [27–30]. Similarly to regime 3 above, emissions from Northern Ireland, the Channel Islands and the Isle of Man are reported separately following regime 1, and freight only flights are allocated to the region of origin.

**Results**

A summary of the emissions apportioned to the regions and DAs of GB, using each of the four methods described above, have been projected onto a map of GB in Figure 1 [111]. The four maps demonstrate how the distribution of emissions across GB changes according to the apportionment regime applied. In particular, regime 1 reflects the concentration of airports in London, the south

![Figure 1. Four maps representing the spatial distribution of international and domestic aviation emissions across Great Britain using four different emissions apportionment methods. This work is based on data provided through EDINA UKBORDERS with the support of the ESRC and JISC. Source: 2001 Census, Output Area Boundaries. Crown© 2003. Crown copyright material is reproduced with the permission of the Controller of HMSO [111].](image-url)
east and north west; regions that host large international airports (e.g., Heathrow, Gatwick and Manchester). Comparing the maps of regimes 2 and 3 highlights the regions with either residents that fly more regularly or attract more overseas visitors than other regions when compared with an equal per capita apportioned method.

The percentage distribution of emissions between the regions and DAs is given in Table 1 to complement the maps. Table 1 further demonstrates the difference that apportionment method makes to regions hosting large airports. Greater London hosts the UK’s largest airport, Heathrow, and together with London City and Biggin Hill, these airports, and therefore, the Greater London region accounts for 55% of GB’s aviation emissions; however, when a consumer-based emissions approach is applied, this share falls to 36.9%. Similarly, the north west’s share of emissions falls from 9.5 to 6.5%, demonstrating that the region’s airports provide aviation services to a much wider catchment area than their host region. Those regions/DAs with smaller airports are allocated a correspondingly smaller proportion of emissions according to the producer based approach; however, it is clear that their residents and visitors do use aviation services and can expect to receive a benefit from this. Wales, for example, as a producer only emits 0.4% of the GB aviation emissions whereas as a consumer this rises to 2%; that said, Wales has the smallest proportion of aviation emissions of GB.

The consumer emissions are dominated by Greater London and the south east, which, combined, account for over 50% of emissions using this approach, despite housing only 29% of the GB population. Compared with an equal per capita allocation, these regions emit more than what would be their share of aviation emissions if distributed on an equal per capita basis.

Finally, Table 2 provides the emissions attributable to Northern Ireland, the Channel Islands and the Isle of Man using apportionment regime 1 for comparison. When compared with the ‘producer’ based totals of regime 1 Northern Ireland, the Channel Islands and the Isle of Man represent 0.9, 0.2 and 0.1% of emissions, respectively. It should be noted that the application of regimes 3 and 4 to the Channel Islands and the Isle of Man are expected to be similar to regime 1 given their geographical location. Additional data on the flight emissions and passenger profiles from airports in Southern Ireland are necessary to complete regimes 3 and 4 for Northern Ireland.

### Discussion

Aviation emission estimates are currently provided for the devolved administrations on a ‘producer’ or territorial basis [25]. The maps provided here compare the choice of this method with alternatives based on three different apportionment regimes: the first assesses the distribution of aviation emissions assuming an equal per capita basis; the second alternative attempts to allocate responsibility for emissions according to the beneficiaries of aviation services – the consumers or end-users; and the third comparator combines both approaches in a hybrid method.

The utility of the different emission apportionment regimes are considered here in relation to two broad criteria; first, how the regime reflects the benefit aviation brings to an area (and thus the potential impact on the

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**Table 1. Percentage distribution of total emissions split between the regions and devolved administrations included in the table using each of the four apportionment regimes.**

<table>
<thead>
<tr>
<th>Region/devolved administration</th>
<th>Regime 1: Producer based (%)</th>
<th>Regime 2: Equal per capita (%)</th>
<th>Regime 3: Consumer (%)</th>
<th>Regime 4: Hybrid producer–consumer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scotland</td>
<td>4.7</td>
<td>8.7</td>
<td>5.0</td>
<td>4.9</td>
</tr>
<tr>
<td>North east</td>
<td>1.3</td>
<td>4.4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>North west</td>
<td>9.5</td>
<td>11.7</td>
<td>6.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Yorkshire and the Humber</td>
<td>0.6</td>
<td>8.7</td>
<td>3.3</td>
<td>3</td>
</tr>
<tr>
<td>Wales</td>
<td>0.4</td>
<td>5.0</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>West Midlands</td>
<td>2.6</td>
<td>9.1</td>
<td>4.3</td>
<td>4.1</td>
</tr>
<tr>
<td>East Midlands</td>
<td>1.6</td>
<td>7.4</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>East of England</td>
<td>5.2</td>
<td>9.5</td>
<td>8.0</td>
<td>7.9</td>
</tr>
<tr>
<td>South west</td>
<td>1.4</td>
<td>8.7</td>
<td>6</td>
<td>5.5</td>
</tr>
<tr>
<td>South east</td>
<td>17.3</td>
<td>14.0</td>
<td>22.3</td>
<td>22.9</td>
</tr>
<tr>
<td>Greater London</td>
<td>55.4</td>
<td>12.8</td>
<td>36.9</td>
<td>37.4</td>
</tr>
</tbody>
</table>

**Table 2. Emissions associated with Northern Ireland, the Channel Islands and the Isle of Man following option 1 compared with total UK aviation emissions.**

<table>
<thead>
<tr>
<th>CO₂ kt</th>
<th>% of total UK emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Ireland</td>
<td>296.5</td>
</tr>
<tr>
<td>The Channel Islands</td>
<td>61.4</td>
</tr>
<tr>
<td>The Isle of Man</td>
<td>27.6</td>
</tr>
</tbody>
</table>
area of future constraints or carbon price on aviation); and second, its potential effectiveness in monitoring local emission mitigation measures. In addressing benefit to an area, issues such as economic benefit or otherwise to the region, use of the airport by residents and non-residents and consumption of aviation outside of the region are important to address. From an effectiveness point of view, the apportionment regime's potential to monitor suitable emission mitigation efforts at this scale is discussed together with the information the results provide on the relative emphasis that should be placed on such efforts.

First, in considering the benefits that aviation brings to a region and how this is captured by the regime, benefits are both monetary and non-monetary. The economic benefit of aviation to a region can be grouped into three sources:

- Direct contribution of employment and gross value added (GVA) to the area from both airports and airlines.
- Catalytic effects on the economy through supporting inbound and outbound tourism, investment, international trade and sectors with a high dependence on aviation service.
- As a trigger of growth and productivity in general [15].

The direct contribution of both airports and airlines to national and regional GVA is reported annually in the Annual Business Survey. The impact is relatively straightforward to obtain from publicly available data [112]. However, both the methods and data used to estimate the economic contributions of the catalytic and wider effects, predominantly associated with the services provided by aviation, are the subject of debate [32,33]. Furthermore, at a regional or DA level the data do not exist to undertake a robust analysis of these impacts [15,33,34]. To ascertain the benefit to the region or otherwise of the catalytic and wider effects we therefore turn to the consumers of aviation. If not bringing an economic benefit, they may receive nonmonetary benefits from, for example, having a holiday or visiting friends and relatives; impacts that are far harder to quantify. It is assumed in this discussion that those who fly perceive some form of benefit, monetary or otherwise, from doing so and therefore that the regions/DA that they either reside in or visit also benefit. Following the benefit–principle emissions could therefore be deemed attributable to such beneficiaries [20]. In order to assess how a region benefits from aviation, important considerations include the presence and size of an airport(s) within the region and the extent to which a region’s residents and visitors use aviation services.

In terms of the mitigation measures available for delivery at a regional and DA level, the regimes can be divided into those that target the growth rates of aviation and those that aim to reduce the emissions intensity of aviation. The role of regions and DAs in supporting growth in aviation is outlined above, rethinking current activities to align with recommended targets is an important step in counteracting the very high growth rates observed historically [2]. Managing demand from aviation is challenging, with a number of studies finding that existing and proposed economic measures that increase the cost of a flight have a limited impact on reducing demand for aviation by tourists [35], despite this group of travelers reportedly showing the most price elasticity [36]; suggesting alternative and complementary measures should also be considered. Passenger studies suggest a strong correlation between higher income and air travel emissions [37,38], and growth in UK air travel is predominantly the result of those in higher income categories flying more often [38]. This suggests mitigation policies should be targeted at these high level users, more readily identifiable at a regional or local level than by national government. Although economic interventions may not be appropriate for local and regional governance, complementary strategies may include the promotion of domestic tourism and activities to break the perception that nondomestic holidays are superior to domestic ones [8,36–38]. In terms of flying for business, which accounts for approximately 20% of air passenger travel in the UK [39], some studies suggest 20% of business travel may be avoided through, for example reducing unnecessary trips or substituting to video conferencing [39]. The Icarus project aims to provide businesses with advice on ways to reduce the carbon emissions produced through business travel [40]. Crucial to the uptake of information communication technologies (ICT) will be the provision of high speed internet connections and access to ICT facilities and technical knowledge; an area under the gift of both Local Development Frameworks and Regional Spatial Strategies.

Measures aimed at reducing the emissions intensity of aviation are at the behest of airports and airlines. Airports are currently encouraged to assist emissions reduction of the LTO cycle through stage 3 of the airports accreditation scheme [113]. Working with airlines and National Air Traffic Services (NATS) through, for example, ‘collective environmental management’ schemes [41]. Their current options include assisting the reduction of inefficiencies during air traffic movements and the elimination, where possible, of the use of auxiliary power units [42,43]. In the future, airports may also wish to consider how the airport design can accommodate new low carbon aircraft. Local ‘governance’ systems integrating activities between public, private and NGOs can all assist airports and airlines to implement the most efficient operational practices. Each of the regimes is now discussed in turn in regard to
how the regime reflects the benefit that aviation brings to an area (and thus the potential impact on the area of future constraints or carbon price on aviation) and, second, its potential effectiveness in monitoring local emission mitigation measures.

- **Regime comparison**
  
  Regime 1 accounts for the different types of flight departing from a region’s airports compared with other regions and duly highlights where GB’s major airports are located. It can be used to indicate the liability of airlines operating out of a region’s airport to future carbon constraints. In terms of ‘benefit’ it reflects the direct economic benefit that an area that hosts an airport receives. However, when defined narrowly in terms of GVA provided by airports and airlines, this does not necessarily reflect the full economic impact of the sector [44]. There are wider impacts, indirect and catalytic, which principally arise from the service users. Whereas an area may well serve its local residents and attract visitors, the apportionment method does not fully account for the use of other airports by its own residents and includes the use of its airports by consumers from other regions.

  Mitigation measures to address aviation to be monitored using this metric would be most effective if directed at the producer of those emissions rather than the consumer. The problem here is that while moderate reductions in emissions per flight can be achieved through, for example, green descent and ascent and reducing take-off weight, the technological options for reducing emissions significantly within the short-medium-term timescale are severely limited [2,45] and are often outside of the ability of local aviation governance to influence. If restrictions were to be placed upon future growth in passenger number as advised by the CCC [2] this metric would not entirely capture the travel behavior of a region’s residents and visitors. As found in regimes 3 and 4, many airports provide services to a much wider catchment area.

  Regime 2 enables a comparison to be made of the consumer-based regime with an equal per capita distribution of aviation emissions across GB, it can be used to identify regions/DAs that consume lower or higher aviation services than what would be suggested by their equal per capita share. It is a method that is often used as a simple proxy to downscale emissions from national totals to sub-national levels; by comparison with regimes 1 and 3 it is demonstrable that this regime is not suitable for aviation since it does not reflect either the producer-based method or the consumer-based method.

  Regime 3, the consumer, end-user approach, reflects the geographical distribution of those who benefit from the use of aviation services and the regions whose consumers would be impacted most by constraints on aviation. This metric would enable the region to monitor the effect of efforts aimed at reducing the rate of demand growth for aviation services by residents and visitors to a region; it could, for example, be used to monitor the success of tourism strategies or ICT deployment in reducing air travel demand. However, by considering only the origin of consumers of a journey, this metric does not adequately reflect economic and broader benefits of hosting an airport. In essence it attributes emissions only to those who fly, making no allowance for wider benefits arising from, for example, the employment opportunities and GVA advantages to a region of operating an airport and its associated infrastructure. Therefore, the use of this metric offers no significant incentive for a region to address the emissions burden associated with its airport(s) and, moreover, if the region takes the view that hosting an airport is economically beneficial, there is no ‘carbon constraint’ or penalty to expansion.

  Regime 4 is intended to provide an allocation of emissions that in part reflects the direct economic benefit to a region of hosting an airport and also of the benefits from its consumers and a metric that can measure the implementation of a wider set of appropriate policy levers to reduce emissions. This regime does not unduly penalize a region from a producer-perspective for simply hosting an airport, as is the case for regime 1. Furthermore, it takes into account its own region’s propensity to fly and acknowledges that regional benefits accrue from inbound tourists and business contacts. On the producer-side of the hybrid approach, efforts to reduce LTO inefficiencies, such as managing on-ground taxiing and hold times, as well as facilitating the continuous descent approach and providing alternatives to APUs, could be monitored using this metric, with sufficient local data capture [42]. At the same time, the region could explore policies for providing alternative lower carbon intensive transport to reduce the growth (or the absolute level) of its residents’ cruise emissions; for example, by encouraging airlines with a more efficient fleet to use their airport [46]. The metric also enables the success of policies aimed at reducing the growth rate of consumer demand from the region as in regime 3. Given the scale of the climate change challenge and the barriers to significant near-term technological opportunities for aircraft, this hybrid regime provides a metric that can assess a wider set of mitigation options.

  The information provided by the regimes, when considered together, enable a region to identify the relative size of their contribution to GB’s aviation emissions and the scale of potential impact of future constraints on aviation emissions. This information can be used to develop both targeted emission reduction activities and to take steps to mitigate the impact of aviation emission constraints on the region’s economic and social well-being.
Conclusions
The article presents the methodologies for applying four different emission apportionment regimes to divide aviation emissions between GB’s regions and Devolved Authorities. Each regime offers different insights into the contribution of the region/DA to GB’s aviation emissions. The regimes demonstrate the variations between regions/DAs that currently hold the emissions ‘burden’ of hosting an airport with alternatives that attempt to also reflect a region’s role as a consumer of aviation services as demonstrated in Figure 1. Following a purely producer- (or ‘polluter’) based allocation principle, Figure 1 regime 1 reflects the location of GB’s large airports, dominated by Greater London, the south east and north west, whereas Figure 1 C regime 3 reflects the areas of GB that either attract visitors or whose residents fly. Again this is dominated by Greater London and the south east; however, emissions are more widely distributed between the regions/DAs when applying this approach.

The choice of the apportionment regime to use, by a region/DA resides with those bodies public or otherwise that commission emission inventories. When making the choice of apportionment regime it is important to consider what the metric reflects and whether it is capable of monitoring the impact of local decarbonization activities in future years. Here, apportionment regime 1 can monitor the impact of measures aimed at reducing the emissions intensity of aviation; regime 3 can monitor the impact of measures aimed at the consumers of aviation services. Regime 4 attempts to provide a metric that combines both, capturing measures aimed at reducing the carbon intensity of aviation that are most amenable to delivery at a regional level – improvements in the efficiency of the LTO stage and also of the amount of aviation services used by visitors to and residents of the area.

The importance of addressing aviation emission apportionment at a sub-national scale cannot be overstated. In January 2009 the Government set a target that UK aviation emissions of CO2 in 2050 should not exceed 2005 levels [2]. To deliver this target, the CCC have advised that the level of aviation passenger demand increase should be limited to a maximum of 60% on 2005 levels by 2050 [2]. Despite the recent economic downturn and corresponding reduction in aviation emissions and passenger numbers in 2008–2010, many reports expect levels of growth to return to pre-recession levels when the economy returns to growth [3,47]. This highlights the importance of delivering measures, which limit future growth in demand, targeting the end-users of aviation in the UK, in conjunction with mechanisms to deliver emissions intensity improvements. Regions, DAs and their corresponding local authorities and wider institutions already have a demonstrable influence on emissions from the aviation sector [8,9,102,103,105]. These existing influences have the potential to assist in the reduction of emissions from aviation and a corresponding metric is required to both monitor their efforts and enable the area to anticipate the future impacts of emission constraints not only on aviation but other associated and dependent economic activities too.

Future perspective
Future work in this area is likely to include the development of two key areas: first, improved sub-national data collection will enable the use of more sophisticated and dynamic CO2 emissions-monitoring mechanisms to support carbon management; and second, the wider use of consumer data to enhance understanding of both the demand that underpins the use of carbon intensive activities and the associated economic impacts. Improving the understanding of the dynamics behind both emissions intensity and demand can be used to identify further policy measures that can be implemented at this level of governance to support the sector’s mitigation efforts while protecting economic benefits.

Improvements in sub-national data on emissions sources can assist the delivery of emission reductions from all sectors in the future. This will become important as ‘no regrets’ policies achieve their desired outcomes and additional emissions savings are required but that are harder to identify from our current datasets. For example, the emissions estimation methods used in this article rely on the use of fuel consumption rates that, while specific to thrust setting and aircraft type, do not capture the full range of factors that may have an impact on fuel consumption. The use of such generic fuel consumption factors that embed within them a host of operating conditions precludes the ability to model emission reduction options in great detail. If used without cross reference to actual fuel consumption they can fail to effectively monitor future mitigation efforts. At present, these shortcomings in emissions and activity data cannot yet be overcome and are by no means limited to the aviation sector at the local level.

As airlines participate in the EU ETS, the ability to monitor fuel savings from, for example, reducing take-off weight, green descent and ascent and speed and route optimization will become important. Existing publicly available models do not have the sophistication required to incorporate these changes in their calculations. The inclusion of aviation into the EU ETS not only requires airlines to monitor their fuel consumption but may also provide the economic incentive to examine potential for fuel savings available during different flight stages. Work by Reynolds et al. highlights the inefficiencies in current...
The methods used to apply the four regimes to aviation emissions in Great Britain are presented using data sourced from the Civil Aviation Authority. As noted in the article, demand management has been identified as important in delivering aviation’s emission targets; similarly, demand management has also been identified as necessary for reducing emissions from other sectors such as road transport. Targeting measures to reduce end-use consumption requires an understanding of who is consuming and why, as well as how the consumption brings benefits to the area, economic or other. Carbon management approaches that can capture these dynamics will become increasingly useful, particularly if carbon constraints lead to restrictions on passenger numbers. Identifying aviation users that bring the most economic and social benefit to the region could be used to protect a region from any negative impacts of future constraints. The maps presented here provide an indication of the spatial location of high-end aviation consumers at present. Measures aimed at reducing consumption could be targeted in the first instance at these areas; however, enhancing the understanding of these consumers through greater market segmentation may avoid the pitfalls of blanket measures.

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Executive summary

Introduction
- Controlling aviation emissions in line with UK Government targets requires both a reduction in the emissions intensity of aviation and commensurate demand management.
- Sub-national action can complement and support the delivery of measures to reduce the emissions intensity of the sector and commensurate demand control. To do this, sub-national areas require an understanding of the proportion of Great Britain’s aviation emissions that they can influence.
- The article compares a number of apportionment regimes that can be used to apportion aviation emissions to sub-national areas and provides a commentary on how the results can be interpreted and used in the future.

Methodology
- The methods used to apply the four regimes to aviation emissions in Great Britain are presented using data sourced from the Civil Aviation Authority.

Discussion & conclusions
- A ‘producer-based’ approach provides a baseline from which technological and operational improvements can be monitored; for example, from local initiatives to reduce fuel consumption during take-off and landing or to improve the efficiency standards of aircraft using a local airport.
- An ‘end-user’- or ‘consumer’- based approach can provide a baseline from which to monitor changes in flying frequency of regional residents and visitors and can enable demand-led measures to be monitored; for example, from domestic tourism strategies, rail network improvements and the provision of high end video-conferencing facilities.
- The hybrid ‘producer–consumer’ method provides a baseline and monitoring approach that is capable of reflecting both measures to reduce the emissions intensity of the sector and to control demand.
- Both end-user and producer-based emissions apportionment methods highlight the disproportionately high (when compared with an equal per capita split of emissions) levels of aviation emissions that can be attributed to London and the south east. The cooperation of these regions will be fundamental to the delivery of the national target.

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