10.5 Decarbonization of aviation

Aviation is widely recognized as a 'hard-to-decarbonize' sector (Sudhir Gota, Huizenga, Peet, Medimorec, & Bakker, 2019c) (Committee on Climate Change, 2019) having a high dependency on liquid fossil fuels and an operational and technology infrastructure that has long 'lock-in' timescales, resulting in slow fleet turnover times and long technology development timescales. Alternative lower-carbon footprint fuels have been certified for usage over recent years, principally from bio-feedstocks but are not yet widely available at economic prices yet (Kandaramath Hari, Yaakob, & Binitha, 2015). In addition, alternative fuels from bio-feedstocks have variable carbon footprints because of different life-cycle emissions associated with different production methods and associated land-use change (de Jong et al., 2017b) (Staples, Malina, Suresh, Hileman, & Barrett, 2018b) (Witcover, Yeh, & Sperling, 2013) (Staples, Malina, & Barrett, 2017b) – see section 10.3.3. The complex options emerging will be reviewed.

10.5.1 Historical and current emissions from aviation

The principal greenhouse gas from aviation is CO_2, although aviation has a number of other effects on climate through its non-CO_2 emissions (see section xx). Emissions of CO_2 are calculated under UNFCCC reporting requirements as being either domestic or international; however, a number of methodologies are used by states according to facilities and data availability such that the global data are less reliable for assessment purposes. The International Civil Aviation Organization (ICAO) emissions estimation uses more complex greenhouse gas emissions models (tier 3 models, IPCC, 2006) and datasets of real aircraft movements, where available, and probably represents the best inventory available for spot years (e.g. 2006, 2013). However, ICAO focusses on international emissions and there are some known sources of underestimation. Historical data are required for assessment of CO_2 impacts and this has been estimated from International Energy Agency (IEA) statistics of aviation fuel (Jet-A1, AvGas) production and usage (Sausen & Schumann, 2000) (Lee et al., 2009) (Lee et al., 2020).

Domestic aviation emissions are attributable to states and are included under their NDCs towards the Paris Agreement goals, whereas international emissions are non-attributable to states (similar to international shipping emissions). International emissions of CO_2 from aviation are not specified under the Paris Agreement (unlike the Kyoto Protocol), however, the respective UN agencies of ICAO and the International Maritime Organization are still pursuing measures for limiting and reducing emissions of greenhouse gases.

In 2018, emissions of CO_2 from global aviation were just over 1 Gt of CO_2 and have been steadily increasing at rates of around 2.5% yr^{-1} over the last two decades although the period 2010 to 2018 saw a sharper increase of +27% in total. International emissions of aviation are calculated by ICAO to be 65% of global emissions and projected to increase both in absolute terms and as a relative proportion to total aviation (Fleming & Lepinay, 2019). Current (2018) total CO_2 emissions from aviation represent approximately 2.4% of total anthropogenic emissions of CO_2, including land use change, on an annual basis (using IEA data, IATA data and global emissions data, Le Quéré et al., 2018).

10.5.2 Short lived climate forcers and aviation

Aviation emits a number of gases and aerosol particles that contribute towards its total fraction of anthropogenic climate forcing of approximately 3%, from its historical emissions of CO_2 and other emissions of water vapour, particles from soot and sulphate (from S in the fuel), and nitrogen oxides (NOx, $=NO + NO_2$), with its 2018 total being ~98 mW m^{-2} (Lee et al., 2020). The non-CO_2 effects of aviation on climate fall into the category of short-lived climate forcers (SLCFs). Emissions of water vapour and soot particles can trigger the formation of contrails, if the atmosphere is supersaturated with respect to ice, and below a critical threshold temperature condition (Kärcher, 2018). These linear contrails can spread to form extensive contrail cirrus cloud coverage, which is estimated to have a combined effective radiative forcing (ERF) of around 50 mW m^{-2} (Lee et al., 2020), some 51% of the current ERF of global aviation. Emissions of NO_x result in an enhancement of short-lived O_3 (a positive ERF) and a reduction of ambient CH_4, which represents a negative ERF; the CH_4 reduction also results in negative ERFs from reductions in stratospheric water vapour (Myhre et al., 2007) and background O_3 (Holmes, Tang, & Prather, 2011), which together results in a net NO_x ERF of ~18 mW m^{-2} (Lee et al., 2020).

Additional effects from aviation from aerosol-cloud interactions are thought to exist but the magnitude of these are highly uncertain, with no best estimates available. Soot emissions from aircraft, either deposited directly in the atmosphere or sublimed from contrail cirrus may increase cloudiness, and the forcing from this cloudiness may be strongly negative or positive, depending on critical atmospheric parameters (C. Zhou & Penner, 2014) (C. Zhou, Penner, Lin, Liu, & Wang, 2016), or possibly closer to a zero net effect (Gettelman & Chen, 2013) (Pitari et al., 2015). Sulphur from the fuel is largely emitted as SO_2 with a small fraction (~3%) emitted as H_2SO_4 (Petzold et al., 2005). The SO_2 oxidises in the background atmosphere to form sulphate particles, and these particles are thought to contribute to the secondary indirect effect on warmer low-level liquid clouds, resulting in a net negative forcing of uncertain magnitude (Righi, Hendricks, & Sausen, 2013) (Kapadia et al., 2016).

The net warming from aviation's non-CO_2 SLCFs is ~64% of aviation's total warming and as such is the subject of discussion for reducing its impacts. However, the issues are complex, potentially involving technological, operational and atmospheric trade-offs with CO_2 (see section X). Moreover, the impacts of aviation NO_x emissions perturbing the chemical composition of the atmosphere are not independent of background emissions from surface sources (ozone precursor emissions of NO_x, CO, CH_4 and NMHCs) and need to be accounted for in assessing future changes in ERF and mitigation potential (Skowron et al., 2020).

10.5.3 Mitigation potential of fuels, operations, energy efficiency and market-based measures

Technology options (engine/airframe)

The principal GHG of importance from aviation is CO_2, emitted at a ratio of 3.16 kg CO_2 for every kg of fuel combusted. Other emissions that impact on aviation's non-CO_2 effects on climate are water vapour, particles, and NO_x (10.5.1). Engine and airframe manufacturers primary objective after safety issues is to reduce direct operating costs, i.e. fuel burn so much investment has gone into engine technology and aerodynamics to improve fuel burn per km. there have been major step changes in emgine technology over time, e.g. from early 'jet' (turbojet) engines, to larger turbofan engines, and second-generation turbofans. Airframes have had improved performance over the years with wing design and incorporation of 'winglets' on the wing-tips. However, the basic configuration of an aircraft has remained more or less the same for decades.

As a result of this continuous improvement, large incremental gains have become much harder as the technology has matured, although twin-aisle aircraft have seen greater improvement rates in their lift to drag ratio than those of single-aisle aircraft (Cumpsty et al., 2018). The principal opportunities for fuel reduction come from improvements in aerodynamic efficiency, aircraft mass reduction, and propulsion system improvements. In terms of the future, Cumpsty et al.'s (2018) comprehensive assessment suggested that the highest rate of fuel burn reduction achievable for new aircraft was about 1.3% per year, which short of ICAO's aspirational goal of 2% global annual average fuel efficiency improvement. Hence, the case established in the technology assessment of the IPCC (1999) report on Aviation and the Global Atmosphere is that growth continues to greatly outpace emission reductions from improved efficiency, which is why alternative approaches have been sought to reduce aviation's climate impact by, e.g. alternative lower-carbon fuels on a life cycle basis (next section). More radical solutions have been suggested to modify the current air traffic system, e.g. by 'formation flying' (Xu et al., 2014), which has the potential to reduce fuel burn by up to ~8%. However, this would require increased capability onboard safety systems for wake sensing (Hemati et al., 2014) and ground-based air traffic control.

Operational improvements (navigation)

Aircraft navigation, from a global perspective is relatively efficient, with many long-haul routes travelling along great circle trajectories, or as close to possible, avoiding headwinds that increase fuel consumption (e.g. the north Atlantic flight corridor). In more densely populated and trafficked regions, aviation is more constrained; often by military airspace, congestion or adverse weather (e.g. Europe, North America). Few independent assessments are available of the potential for operational improvements. The ICAO 'trends assessment' exercise (Fleming & Lepinay, 2019), projects global improvements introduced by operational improvements (air traffic management) by an unspecified amount by 2050[1]. In contrast, such projections have to be balanced against detailed assessments of the challenges of operating in more congested airspace: for example, EUROCONTROL (2018) projected in their 'most likely' growth scenario, 'Regulation and Growth', that the majority of en-route airspace will face an increase of demand over 2017 levels by between 50% and 80% by 2040.

Fuels (alternative biofuels, synthetic fuels and liquid hydrogen)

The development of bio-based 'sustainable alternative fuels' has been widely addressed in recent years as a 'drop in' alternative fuel to reduce aviation's carbon footprint. This obviates difficulties over developing radical new or alternative technologies in terms of engines and airframes, which would still utilize fossil-based kerosene aviation fuel. The cost of replacing the 2012 global aviation fleet was estimated at a trillion dollars, taking at least 14 years highlighting the difficulties associated with fleet replacement for new technologies (Hileman and Stratton, 2014). Thus, alternative fuels that can be utilized with current technologies, is an attractive proposition for CO_2 mitigation. Alternative aviation fuels to fossil-based kerosene have to be certified to the same standard as Jet-A for a variety of parameters associated with safety issues. Currently, the American Society for Testing and Materials (ASTM International) has certified five different types of sustainable aviation fuels with maximum blends ranging from 50% to 10% (Chiaramonti, 2019).

Bio-based fuels can be created by a number of feedstocks including cultivated feedstock crops, crop residues, municipal solid waste, waste fats, oils and greases, wood products and forestry residues (Staples et al., 2018). Each of these different sources can have different associated life-cycle emissions, such that they are not net zero-CO_2 but have associated emissions of CO_2 or other GHGs from their production and distribution. There are many challenges and barriers to widespread development of sustainable alternative fuels (SAF), the primary one being the current cost of fossil fuel vs SAF production (SAF is currently around three times the price of kerosene, Hari et al., 2015), which is a constraint on commercial development and viability. Other factors include cost effective production, feedstock availability, and certification costs (Hari et al., 2015). In addition, associated land use change emissions can be as large, or larger than the other life cycle emissions, depending upon crop type and location and represent a constraint in biofuel mitigation potential (Staples et al., 2017) and have inherent large uncertainties (Plevin et al., 2009). Other sustainability issues include food vs fuel arguments, water resource usage, and impacts on biodiversity.

Nonetheless, bio-based SAFs have been estimated to achieve life-cycle emissions reductions ranging between approximately 2% and 70% under a wide range of scenarios (Staples et al., 2018). For a set of European aviation demand scenarios, Kousoulidou and Lonza (2016) estimated that the demand in

---

[1] Estimated from their Figure 4 as a saving of approximately 7% fuel over a baseline, by 2050.

2030 would be ~100 Mtoe in 2030 and biokerosene (HERFA/HVO) penetration would be just over 2% of the total fuel demand at that date.

Clearly, for bio-based SAFs to be economically competitive, large adjustments in prices of fossil fuels or introduction of policies are required. Staples et al. (2018) estimated that in order to introduce bio-based SAFS that reduced LCA emissions by >50% by 2050, prices and policies were necessary for incentivization and require 268 new biorefineries per years and capital investment of approximately 22 to 88 billion US$ (2015 prices) per year between 2020 and 2050.

Other pathways have been discussed for the production of SAFs such as power-to-liquid pathways (Schmidt et al., 2018), sometimes termed 'electro-fuels' (Goldmann et al., 2018), or more generalized power to 'x' pathways (Kober et al., 2019). This process would involve the utilization of renewable electricity, CO_2 and water to synthesize jet fuel. Hydrogen is produced via an electrochemical process, powered by renewable energy and combined with CO_2 captured directly from the atmosphere and combined either by the Fischer-Tropsch or methanol synthesis. In comparison to bio-SAF production, the process is in its infancy but in terms of environmental performance, assuming availability of renewable electricity, it has much smaller land and water requirements, and potential for large life cycle emission reductions (Schmidt et al., 2016). No trials have yet been achieved.

Liquid hydrogen (LH_2) as a fuel has been discussed for aeronautical applications since the 1950s (Brewer, 1991) and a few experimental aircraft have flown using such a fuel. Although the fuel has an energy density ~3 times greater than kerosene, it has a much lower energy density per unit volume. Experimental small aircraft have also flown using hydrogen fuel cells. LH_2 is a viable fuel source for commercial civil aviation passenger aircraft albeit with altered airframe structures to accommodate the fuel in the fuselage (Klug and Faass, 2001). Bicer and Dincer (2017) found that LH_2-powered aircraft compared favourably to conventional kerosene-powered aircraft on a life cycle analysis (LCA) basis, providing that the LH_2 was generated from renewable energy sources (0.014 kg CO_2 tonne km^{-1} cf 1.03 kg CO_2 tonne km^{-1}, unspecified passenger aircraft). However, Pereria et al. (2014) also made a LCA comparison, and found much smaller benefits of LH_2-powered aircraft (manufactured from renewable energy) compared with conventional fossil-kerosene, the two studies exposing the sensitivities of boundaries and assumptions in the analyses. Harsha (2014) and Rondinelli et al. (2017) conclude that there are many infrastructural barriers but that the environmental benefits of renewably-sourced LH_2 would be considerable. Khandelwal et al. (2013) take a more optimistic view of the prospect of LH_2-powered aircraft but envisage them within a hydrogen-oriented energy economy.

In conclusion, there are many favourable arguments for LH_2-powered aircraft both on an efficiency basis (Verstraete, 2013) and an overall reduction in GHG emissions, even on an LCA basis, but the major constraint is the infrastructural issues associated with fuel storage and distribution at airports, which is unlikely to be overcome unless there was a more general move towards a hydrogen-based energy economy. This is a conclusion for most heavy vehicle systems and the hydrogen option.

Technological and operational trade-offs of non-CO_2 emissions and effects with CO_2

Since aviation has significant non-CO_2 warming impacts, there has been some discussion as to whether these can be addressed by either technological or operational means. For example, as aircraft engines have improved their fuel efficiency, with widescale usage of large high overall pressure ratio engines with large bypass ratios from large fan-bladed engines, this has tended to increase pressures and temperatures at the combustor inlet, with a resultant increase in tendency for thermal NO_x formation in the absence of combustor technology to reduce this. This represents a potential technology trade-off whereby NO_x control may be at the expense of extra fuel efficiency. Estimating the benefits or disbenefits of fuel and therefore CO_2 vs NO_x is complex (Freeman, Lee, Lim, Skowron, & De León, 2018), requiring climate/chemistry model calculations and usage of emissions-equivalency metrics, such as the Global Warming Potential (GWP) or Global Temperature change Potential (GTP) (see (Dalsøren et al., 2013) for an overview). Any GWP/GTP type emissions equivalency calculation always involves the user selection of a time horizon, over which the calculation is made, which is a subjective choice (Fuglestvedt et al., 2010). In general, the longer the time horizon, the more important CO_2 becomes in comparison with a SCLF.

A widely discussed opportunity for aviation non-CO_2 mitigation is the avoidance of contrails. Contrails only form with the emission of water vapour and soot particles from aircraft into ice-supersaturated air below a critical temperature threshold (Kärcher, 2018). It is therefore feasible to alter flight trajectories to avoid such areas conducive to contrail formation, since these 'moist lenses' tend to be 10s of km in the horizontal and only a few 100 metres in the vertical extent (Gierens, Schumann, Smit, Helten, & Zängl, 1997). Theoretical approaches in the literature show that avoidance is possible on a flight-by-flight basis (Matthes et al., 2017). In case studies, it has been demonstrated that flight planning according to *trajectories with minimal climate impact* can substantially (up to 50%) reduce the aircraft net climate impacts despite additional CO_2 emissions (e.g., (Niklaß et al., 2019)). However, such a conclusion of the net benefit or disbenefit depends upon the choice of metric and time-horizon applied. As for the above example of technological trade-offs, there is a tendency for additional CO_2 to cause a net disbenefit for all metrics when longer time horizons are considered.

Market-based measures – EU-ETS, other ETS, ICAO-CORSIA offsetting measure

Market-based measures have been introduced in various regions of the world, based on emissions trading of CO_2, notably in Europe but also for domestic aviation in New Zealand. The other major initiative is within ICAO, the 'Carbon Offset and Reduction Scheme for International Aviation' (CORSIA), agreed in 2016 to commence in 2020.

The European Union (EU) introduced aviation into its CO_2 emissions trading scheme (ETS) in 2012. This initially included flights between the European Economic Area (EEA) states and non-EEA states. However, the extension of the scheme to non-EEA states was highly controversial and in 2014 the EU deferred the inclusion these flights under the so-called 'stop-the-clock' derogation. Currently, the EU-ETS for aviation includes all flights within and to and from EEA states. At around the same time, the International Civil Aviation Organization (ICAO) proposed to develop a global offsetting scheme, which was agreed in 2016 to commence in 2020, the 'Carbon Offset and Reduction Scheme for International Aviation'.

CORSIA has a phased implementation, with with an initial pilot phase (2021–2023) and a first phase (2024–2026) in which states will participate voluntarily. The second phase will then start (2026–2035) in which all states will participate unless exempted. States may be exempted if they have lower aviation activity levels or based on their UN development status. As of 16 July 2019, 81 States, representing ~77% of international aviation activity, intend to voluntarily participate in CORSIA from its outset. In terms of routes, only those where both States are participating are included. There is currently no "third phase" described and the fate of the CORSIA beyond 2035 is unclear.

The fate of the EU-ETS running concurrently with CORSIA is unclear at the moment. The EU-ETS is different to CORSIA in that the former is a cap-and-trade scheme, with airlines purchasing allowances, whereas CORSIA relies on verified offsetting, and exempts some biofuels. The nature of offsetting means that reductions are purchased from other sectors that either withhold from an intended emission, or reforest (Becken & Mackey, 2017), which is unclear that this represents a real reduction in CO_2 emissions.

10.5.4 Accountability and governance options

Under Article 2.2 of the Kyoto Protocol, Annex I countries were called to *"...pursue limitation or reduction of emissions of GHGs not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.*" The Paris Agreement is rather different, in that ICAO (and the IMO) are not named, so that international aviation emissions of CO_2 do not appear to be covered, in that the Paris Agreement deals with states, and their Nationally Determined Contributions (NDCs). This would imply that domestic aviation emissions of CO_2 (currently 35% of the global total) are covered by NDCs but international emissions are not. A number of states and regions have declared their intentions to include international aviation in their net-zero commitments including the UK, France, Sweden, and Norway, with the intentions of the European Union, New Zealand, California and Denmark being as yet unclear but under consideration (Committee on Climate Change, 2019). The Paris Agreement is a temperature-based target, such that it is unclear how emissions of GHGs and other climate forcers that are not included, including those from international aviation would be accounted for. Clearly, this is a less than ideal situation for clarity of governance of international GHG emissions from both aviation and shipping.

The ICAO CORSIA is a part of ICAO's aspirational 'carbon-neutral growth goal, 2020', such that through CORSIA and technological and operational improvements, ICAO aims that international aviation emissions of CO_2 should not grow above 2020 levels. In addition, ICAO has a goal of global annual average fuel efficiency improvements of 2 percent until 2020 and an aspirational global fuel efficiency improvement rate of 2 percent per annum from 2021 to 2050. ICAO also regulates emissions, including those of NO_x, CO, hydrocarbons (HCs) and non-volatile particulate emissions (nvPM) from engines, and recently (2017) adopted a whole-aircraft emissions standard for CO_2. The emissions regulations of NO_x, HCs, CO and nvPM are primarily targeted at protecting air quality in and around airports. However, there has been a working assumption that reducing NO_x will reduce its impacts on tropospheric O_3 formation and its subsequent radiative forcing. In addition, emissions of nvPM or 'soot' are part of the early process of contrail formation and reducing the emissions (number) will reduce the initial number of ice crystal particles in the plume at altitude and reduce the propensity for contrail and subsequent contrail cirrus formation (Kärcher, 2018).

More recently, ICAO has at its 40th General Assembly (October, 2019) requested ICAO's Council to "*..continue to explore the feasibility of a long-term global aspirational goal for international aviation, through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly*". What form this goal will take is unclear until work is presented to the 41st Assembly (Autumn, 2022).

10.5.5 Synthesis: transformation trajectories for the aviation sector

Here, three basic trajectories of development are envisaged that have differing degrees of response to reductions in GHG emissions. Some of the developments are encompassed by global or regional goals while some are more speculative.

A '**business as usual**' (BAU) scenario largely reflects current and projected rates of technology development and policies currently in place. So, for aviation, global fleet fuel efficiency improves at around 1-2% per annum, with operational improvement delivering smaller improvements (since the system is relatively efficient). Market-based measures continue to operate through to at least 2030 in the case of the EU-ETS and 2035 in the case of CORSIA. Nonetheless, demand for aviation continues to increase at rates of somewhere between 5-7% yr^{-1} in terms of RPK. Biofuel continues to make small contributions to aviation energy demand, of somewhere between 2 and 10% by 2050.

An ‘**incremental scenario’** might be envisaged that sees technology developments similar to BAU, but with somewhat improved fuel efficiencies achieved from technology development with greater R&D development but a higher penetration of biofuels and zero-C synthetic fuels from renewables, resulting from greater private and governmental investment and the widening of ‘net-zero CO_2 ambitions’ by individual countries.

A ‘**transformational scenario**’ is one that works towards a target of net-zero CO_2 emissions from the aviation sector. This would be driven by active policies that mandated phase-out of fossil fuel usage by 2050, considerable private and governmental investment in technologies for zero-C synthetic fuels produced from widely deployed new fuel production facilities, powered by renewable energy as part of a wider system promotion and mandating of renewable energy sources, with decommissioning of the fossil-fuel energy supply system. Short haul aviation would also be potentially powered by all- or semi-electric powered propulsion systems. Bio-based lower carbon fuels are regarded as an integral part of such a scenario in the short to medium term, gradually being replaced by zero-C synthetic fuels from renewable resources. The cost of flying may become considerably higher and subsequent demand reduced over a BAU scenario. An alternative to widespread usage of zero-C paraffinic fuels which would equally fall under a transformative scenario is that of LH_2 as a fuel for aviation. This would equally require the H_2 to be generated from renewable energy sources. However, it could be likely that such widespread usage is less likely, as this would require complete fleet renewal and design of airframes and to a lesser degree, the engines, as current airframes could not be converted to take LH_2 fuel. Moreover, this would also require renewal of fuel supply infrastructure to airports. Even if the CO_2 impact could be made to be zero under this scenario, the non-CO_2 impacts remain poorly understood, since the emission index of water vapour would be much higher (×2.6, Ström and Gierens, 2002) than for conventional paraffinic fuels, and contrail and contrail cirrus formation may be of a greater incidence although with possibly lower optical thickness with estimates of RF ranging from ×1.3 to ×0.7 when compared with conventional contrail cirrus RF (Marquart et al., 2005). Potentially, NO_x emissions would be lower, since combustion temperatures may be lower (Khandelwal et al., 2013).

10.6 Decarbonization of shipping

10.6.1 Historical and current emissions from shipping

Maritime transport volume has increased by 250% over the past 40 years, reaching all time high of 11 billion tons of transported good in 2018 (UNCTAD, 2019). Shipping (international combined with domestic and fishing) emitted 938 Mt CO_2 in 2012, accounting for 2.6% of global anthropogenic CO_2 emissions (3rd IMO GHG Study, Smith et al., 2014). International shipping alone accounted for 805 Mt CO_2 in 2012. The estimated total emissions from maritime transport vary (Fig 10.15) depending on data set, and converge on 700 – 850 Mt CO_2 per year over the past decade, corresponding to 2-3% of total anthropogenic emissions, as found by Buhaug et al. (2009), Smith et al. (2014), Olmer et al. (2017), Johansson et al. (2017), DNV-GL (2019), the EDGAR data by Crippa et al. (2019), and the CAMS-GLOB-SHIP inventory by Jalkanen et al. (2014) and Granier et al. (2019). The emissions from international shipping are typically based on AIS data on ship traffic activity. There are a number of challenges in calculating emissions from the global fleet, explaining the range in the estimates in Figure 10.15. Such factors include coverage of AIS satellite data, especially further back in time, neglecting to account weather drag on vessels, in addition to hull fouling, as well as lack of information on vessels, such as technological specifications.