A study of carbon dioxide emissions reduction opportunities for airlines on Australian international routes

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Abstract

According to United Nations Intergovernmental Panel on Climate Change, aviation accounts for 2% of the total global greenhouse gas emissions, with international aviation accounting for 1.3% and by 2050, aviation will account for 3% of total global greenhouse gas emissions. Over the next two decades passenger traffic and air cargo is expected to increase at up to 6% per annum.

International flights generate both visible (e.g. con trails) and invisible (e.g. carbon dioxide, nitrogen oxide) emissions across many countries and legal jurisdictions. International emissions were excluded from the Kyoto Protocol and article 2.2 directed The Parties in Annex I of the Protocol to work through United Nations International Civil Aviation Organisation in limiting and reducing greenhouse gas emissions. In this thesis the focus is on carbon dioxide emissions since it is the largest greenhouse gas component in aviation emissions. Members of International Civil Aviation Organisation have adopted global aspirational goals for international aviation of limiting carbon emissions growth to neutral from 2020, including a yearly 2% fuel efficiency improvement. Members agreed to reduce emissions through non-market based measures such as improvements in airline operations, acquiring and updating to new technology, refuelling with sustainable fuel and implementing a global Market Based Measure scheme. At the 39th International Civil Aviation Organisation Assembly, a global carbon offsetting and reduction scheme for international aviation was presented that will be implemented from 2021.

This thesis seeks to determine what combination of policies can be used to manage and reduce emissions from Australian international aviation.

This thesis commences by estimating the total amount of carbon dioxide and carbon dioxide efficiency of airlines that were serving the Australian international market in 2012. Carbon dioxide efficiency is defined as the amount of carbon dioxide generated for each kilogram of payload flown over a kilometre where payload is the combined weight of passengers, luggage and freight. Qantas, Emirates and Singapore airlines were the top three emitters and AirAsia X and Cathay Pacific achieved the same carbon efficiency of 0.60 grams of carbon dioxide for each kilogram of payload flown over a kilometre and were the two most carbon efficient airlines. AirAsia X and Cathay Pacific utilised the same aircraft type but AirAsia X carried a higher number of passengers in their aircraft that is configured with more seats whereas Cathay Pacific configured the same aircraft with fewer seats but carried a higher amount of freight since Hong Kong is one the busiest airports for freight traffic. Emirates airline had the most carbon dioxide efficient long haul flights but was also the least carbon dioxide efficient on short flights to New Zealand due to low passenger numbers.

Qantas and United flew some of the oldest and least efficient aircraft on long haul and this is reflected in their poor carbon dioxide efficiency and higher emissions.

The thesis then estimates the growth in emissions over the next 20 years and estimates the likely reductions in emissions growth assuming airlines adopt planned or soon to be implemented abatement options (such as changing their operations, retrofitting their existing fleet or purchasing new aircraft). Marginal abatement cost curves are presented wherein new aircraft acquisitions were financed at 2% to 6% per annum and repaid over 12 and 15 years. Analysis reveals that implementing all the abatement options with negative or zero marginal abatement cost where new aircraft are financed at 6% per annum repaid over 12 years will result in 17.1Mt and 33.6Mt of carbon dioxide emissions but if interest rate was reduced to 2% per annum, emissions are likely to be reduced to 16.9Mt and 31.7Mt in 2020 and 2033 respectively. Increasing the load factor on each flight by 10% and combining flights together would further reduce carbon dioxide emissions to 15.4Mt and 28.8Mt in 2020 and 2033 respectively.

The results presented in this thesis have a number of implications for policy makers. Due to Australia's geographical isolation Australia has some of the longest international flights and airlines serving these routes have widely varying carbon dioxide efficiencies. Providing low cost finance at favourable terms will encourage airlines to upgrade to newer more fuel saving aircraft. Defining the carbon dioxide efficiency metric as the amount of carbon dioxide emitted for transporting the combine weight of passenger, luggage and freight adjusted for flight distance, gives a fairer assessment of an airline's fuel/ carbon dioxide efficiency regardless of the airline's business model. Setting a performance standard-based carbon dioxide efficiency metric allows airlines to pick and choose the appropriate means of meeting their commitments. Finally, incorporating target carbon dioxide efficiency into the carbon offsetting and reduction scheme for international aviation provides an additional incentive for airlines not only to reduce emissions but also to improve carbon dioxide efficiency.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Kwong-sang Yin (Candidate)	Designed experiments (100%) Executed experiments (100%) Literature review (100%) Wrote and edited paper (87%)
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Anthony Halog	Wrote and edited paper (3%)

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Kwong-sang Yin (Candidate)	Designed experiments (100%) Executed experiments (100%) Literature review (100%) Wrote and edited paper (87%)
Paul Dargusch	Wrote and edited paper (10%)
Anthony Halog	Wrote and edited paper (3%)

Contributions by others to the thesis

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Statement of parts of the thesis submitted to qualify for the award of another degree

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I would also like to thank my former colleagues at Boeing Research and Technology in Seattle for their encouragement and support. I hope after my graduation I will return to Boeing to continue my research. I hope that the contents of this thesis will make a positive contribution to the sustainable management and expansion of international aviation in the future.

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This PhD has increased my understanding of the importance of international aviation and the difficult problem of decarbonising the international aviation industry.

So when you take your next flight to an international conference, holiday or just visiting family and friends do your bit by choosing efficient airlines, offsetting you emissions and travel light so as to reduce your carbon footprint.

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International aviation, carbon emissions, carbon efficiency, carbon offset, carbon neutral growth, economics, policy, finance.

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Abbreviations and Acronyms

Acronyms	
APU	Auxiliary Power Unit
ATAG	Air Transport Action Group
ATK	Available Tonne-Kilometre
ATM	Air Traffic Management
AVG	Average
BAU	Business as Usual
BITRE	Bureau of Infrastructure, Transport and Regional Economics
bn	Billion
CAEP	Committee on Aviation Environmental Protection
CAPA	Centre for Aviation
CCL	Climate Change Levy
CDM	Clean Development Mechanism
CH_4	Methane
CIRR	Commercial Interest Reference Rates
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Coface	Compagnie Française d'Assurance pour le Commerce Extérieur
Contrails	Condensation trails
COP	Conference of the Parties
CORINAIR	Core Inventory of Air Emission
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DLR	German Aerospace Centre
EEA	European Environmental Agency
EFB	Electronic Flight Bag
EPA	Environmental Protection Agency
ETS	Emissions Trading System
EU	European Union
EU-ETS	European Union Emissions Trading System
EXIM	Export-Import
FAA	Federal Aviation Administration
FTTS	Fibre to the Seat
g	Gram
gal	Gallon
GCD	Great Circle Distance
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTP	Global Temperature Potential
GWP	Global Warming Potential
H_2O	Water
HC	Hydrocarbons
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFE	In-flight Entertainment
Int	Interest
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

Acronyms	
L	Litre
lb	Pound
LRF	Lease rate factor
kg	Kilogram
km	Kilometre
kt	Kilo tonne
m	Metre
MACC	Marginal Abatement Cost Curve
MBM	Market-Based Measure
mil	Million
MS	Microsoft
Mt	Million tonnes
MTOW	Maximum Take-Off Weight
MZFW	Maximum Zero Fuel Weight
NA	Not applicable
nm	Nautical mile
NO_x	Mono-nitrogen oxides
NPV	Net Present Value
OAG	Official Airline Guide
OECD	Organisation for Economic Cooperation and Development
OEW	Operating Empty Weight
Pax	Passenger
R&D	Research and Development
REDD+	Reducing Emissions from Deforestation and forest Degradation in developing countries
RFI	Radiative Forcing Index
RTK	Revenue Tonne Kilometre
SARP	Standards and Recommended Practice
SARS	Sudden Acute Respiratory Syndrome
SBSTA	Subsidiary Body for Scientific and Technological Advice
SO_x	Sulphur Oxides
SRES	Special Report on Emission Scenarios
t	Tonne
tCO_2	Tonnes of Carbon dioxide
tCO_2e	Tonnes of Carbon dioxide equivalent
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollars
WACC	Weighted Average Cost of Capital
yo	Year old
yr	Year

ISO 2-letter country codes	
AE	United Arab Emirates
AU	Australia
HK	Hong Kong
ID	Indonesia
MY	Malaysia
NZ	New Zealand
SG	Singapore
UK	United Kingdom
US	United States of America

UN 3-letter country codes	
AUS	Australia
CHN	China
FIJ	Fiji
GBR	Great Britain
HKG	Hong Kong
IDN	Indonesia
JPN	Japan
MYS	Malaysia
NZL	New Zealand
SGP	Singapore
THA	Thailand
UAE	United Arab Emirates
USA	United States of America

IATA airline codes	
CX	Cathay Pacific
D7	AirAsia X
DL	Delta Air Lines
EK	Emirates
EY	Etihad
GA	Garuda
HA	Hawaiian Airlines
JQ	Jetstar Airways
MH	Malaysia Airlines
NZ	Air New Zealand
QF	Qantas Airways
SQ	Singapore Airlines
TG	Thai Airways
UA	United Airlines
VA	Virgin Australia

IATA 3-letter airport codes	
ADL	Adelaide
AKL	Auckland
AUH	Abu Dhabi
BKI	Kota Kinabalu
BNE	Brisbane
CHC	Christchurch
CGK	Jakarta
CNS	Cairn
DFW	Dallas Fort Worth
DPS	Denpasar
DUD	Dunedin
DRW	Darwin
DXB	Dubai
GUM	Guam
HKG	Hong Kong
HLZ	Hamilton
HNL	Honolulu
KUL	Kuala Lumpur
LAX	Los Angeles
MCY	Sunshine Coast
MEL	Melbourne
OOL	Gold Coast
PER	Perth
PHE	Port Headland
ROT	Rotorua
SFO	San Francisco
SIN	Singapore
SYD	Sydney
WLG	Wellington
ZQN	Queenstown

Chapter 1. Introduction

On New Year's Day 1914, the first scheduled commercial fixed wing flight on an airboat took off from Saint Petersburg, Florida and landed in Tampa, Florida 23 minutes later and cost the mayor of Saint Petersburg US$400.00 (International Air Transport Association (IATA), 2013b). By 2014, the aviation industry directly and indirectly generated US$664.4 billion and US$761.4 billion, respectively, towards the global Gross Domestic Product (GDP) and directly employed 9.9 million people (and 11.2 million indirectly) around the world (Air Transport Action Group (ATAG), 2016). The aviation industry also carried 3.3 billion passengers and, over 50 Mt of cargo, which is 35% of the world's cargo by value and represents US$6.4 trillion invested in the world's airlines. (Air Transport Action Group (ATAG), 2016). The global air transport is growing at a rate of 4.3% per annum, so by 2034 aviation will directly contribute 14.9 million jobs and US$1.5 trillion towards global annual GDP (Air Transport Action Group (ATAG), 2016).

> *"Over the last century, commercial aviation has transformed the world in ways unimaginable in 1914. The first flight provided a short-cut across Tampa Bay. Today the aviation industry re-unites loved ones, connects cultures, expands minds, opens markets, and fosters development. Aviation provides people around the globe with the freedom to make connections that can change their lives and the world."*
>
> Tony Tyler, IATA's Director General and CEO (International Air Transport Association (IATA), 2013b).

According to the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC), aviation accounts for about 2% of the total global greenhouse gas (GHG) emissions (Air Transport Action Group (ATAG), 2016; Barker et al., 2007; IPCC, 1999). In 2015, aviation emitted 781Mt of carbon dioxide (CO_2) with 80% of that attributed to flights over 1500km (Air Transport Action Group (ATAG), 2016). Over the next two decades, passenger traffic in the Asia-Pacific region is expected to increase at an annual rate of up to 6% and international air cargo is expected to grow at up to 5% annually with GHG emissions growing at between 3% to 4% annually (Air Transport Action Group (ATAG), 2016; Airbus, 2012b, 2016a; Barker et al., 2007; Boeing, 2012b, 2016; ICAO, 2010; Ribeiro et al., 2007). Even with more fuel efficient aircraft, aviation will account for 3% of the total global GHG emissions by 2050 (IPCC, 1999). The amount of air travel can be affected by many factors such as the economy (global, regional, national), currency fluctuations, health concerns, political stability, wars, trade liberalisation and airfares. According to Boeing, the growth in air travel is approximately 1.0-2.0% higher than the growth in GDP (Boeing, 2012a, 2016).

International flights generate emissions across many countries and regions, yet aviation emissions were excluded from the Kyoto protocol (United Nations (UN), 1998). Article 2.2 directed the Parties in Annex I of the protocol to work through UN's International Civil Aviation Organisation (ICAO) in limiting and reducing GHG emissions. International aviation was excluded from the 21st Conference of the Parties (COP21) agreements and ICAO will report the results of their environmental work to United Nations Framework Convention on Climate Change (UNFCCC) Subsidiary Body for Scientific and Technological Advice (SBSTA) (ICAO, 2015).

Members of ICAO adopted aspirational goals of carbon neutral growth from 2020 and 2% annual fuel efficiency improvement for international aviation (ICAO, 2013c). These goals are to be achieved through improvements in infrastructure and aircraft operations, advancements in aircraft technology, the deployment of sustainable alternative fuels and global market-based measures (ICAO, 2016c). At the 38th session of the ICAO Assembly in 2013, members agreed to develop and present recommendations on a global market-based measure (MBM) scheme for reducing international aviation emission at the next session (ICAO, 2013a). Almost 20 years after Kyoto, the global MBM presented at the 39th ICAO Assembly in 2016 is a phased implementation of the global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) beginning in 2021. The CORSIA will distribute offset obligations to airlines operating between participating states, based on the airline's share of the total emissions and relative success at meeting a prescribed emission baseline (ICAO, 2016c). Participation is on a voluntary basis from 2021 through to 2026 and, as of October 2016, 66 states (including all the countries in this study, namely Australia, United States of America (USA), United Arab Emirates (UAE), New Zealand, Malaysia, Singapore, Hong Kong and Indonesia) intend to voluntarily participate in the CORSIA from 2021. Emission units and permits generated from mechanism such as the UNFCCC's Clean Development Mechanism (CDM), programs such as Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) or projects such as forestry conservation and renewable energy can be used by airlines to offset their emissions obligations. ICAO's environmental work, including the CORSIA, was presented to the UNFCCC's SBSTA at the 22nd Conference of the Parties (COP22) in November 2016.

Research on an integrative policy for GHG emissions management in international aviation has focused mainly on global, regional (e.g. European Union) or large national (e.g. United Kingdom) markets. These studies consider the problem from the "top-down", ignoring how (current and proposed) policies will affect each individual airline servicing these markets. The literature review discussed in each relevant chapter in this thesis found no studies that focused on airlines servicing the Australian international aviation market. This thesis therefore tackles the research problem "How can airlines on Australian international routes more effectively reduce their CO_2 emissions and improve efficiency?" and does so by answering three research questions:

Research Question 1.	What is the CO_2 emissions profile of airlines operating in the Australian international routes?
Research Question 2.	What emissions abatement options are available to airlines on Australian international routes and what is the impact on the future CO_2 emissions profile? What are the marginal abatement costs and what is the impact of low-interest finance?
Research Question 3.	What integrative policies could facilitate more effective emissions outcomes on the Australian international routes?

Chapter 2 provides a general literature review of the numerous aviation stakeholders, emission abatement options, policy instruments and obstacles that have an impact on aviation emissions. It outlines how governments (directly and indirectly) have nurtured and regulated the development of the aviation industry and how policy makers are attempting to control the growth in aviation emissions.

Chapter 3 gives an overview of how the thesis methodology meets the overall research objectives. This chapter summarises how each stage of the methodology produced key results that answered the three research questions.

Chapter 4 provides the CO_2 emissions profile of airlines operating on the most populous Australian international routes in 2012. These routes are between Australia and the USA, UAE, New Zealand, Malaysia, Singapore, Hong Kong and Indonesia. An airline's CO_2 emissions profile is made up of the amount of CO_2 emitted and CO_2 efficiency (i.e. the amount of CO_2 emitted for each passenger per kilometre flown and CO_2 emitted for each kilogram of payload per kilometre flown). Payload is the combine weight of passengers, luggage and freight. This is the first study to combine both passenger and freight when calculating the efficiency of each airline, which is useful in developing performance metric that can be used in policy instruments. Chapter 4 concludes by briefly discussing the need to perform additional research on the effect each abatement option has on both CO_2 emissions and CO_2 efficiency for each airline. This chapter was published in the *Journal of Air Transport Management* (Yin, Dargusch, & Halog, 2015).

Chapter 5 determines the increase in CO_2 emissions of airlines operating on the most populous Australian international routes as passenger and freight traffic increases over the next 20 years.

Some airlines on Australian international routes have announced a number of emissions abatement options that will be implemented over this period. This chapter estimates the change in CO_2 emissions and CO_2 efficiency as airlines implement a number of these abatement options. The results show the maximum amount of emissions that would be abated and the further reduction of emissions still needed from all flights in order to stay carbon neutral after 2020. Chapter 5 concludes by discussing the need to determine the financial viability and ease of implementation of each abatement options for each airline. This chapter was published in the *International Journal of Sustainable Transportation* (Yin, Dargusch, & Halog, 2016).

Chapter 6 determines the financial viability of each abatement option presented in Chapter 5 for each airline. The costs of all abatement options are adjusted for inflation, with some abatement costs recurring regularly over the next 20 years due to obsolescence and wear and tear. This chapter pays special attention to the total cost of acquiring new fuel-efficient aircraft by building a cost model that takes into consideration inflation, maintenance, loan, depreciation, residual and lease cost of each aircraft type. The model was used to determine the savings in fuel cost for each abatement option over the next 20 years. Marginal abatement cost curves (MACCs) are produced and the CO_2 emissions profile are updated, assuming that airlines implement only the financially viable abatement options (an abatement option is deemed financially viable if it has negative or zero marginal abatement cost). This chapter also considers how obtaining favourable finance can increase the number of new aircraft in the fleet, subsequently reducing total emissions and improving CO_2 efficiency. Chapter 6 concludes by discussing that Australian-based airlines sometimes use the same aircraft for both domestic and international flights, so more accurate MACCs should include both the domestic and international fleet. This chapter is currently under review with the *International Journal of Sustainable Transportation*.

Chapter 7 reviews the global market-based measure for international aviation in the form of the CORSIA that was presented at the 39^{th} ICAO Assembly in 2016. This chapter presents an improvement to the formula used to calculate the carbon offset obligations for each airline in the CORSIA by taking into consideration an airlines relative success at meeting or exceeding the yearly CO_2 efficiency target. The CO_2 efficiency target allows airlines to choose the most appropriate means for meeting the efficiency benchmark.

Chapter 8 presents the carbon offset obligations for airlines servicing the Australian international routes using both the ICAO's CORSIA and the improved carbon offset scheme (presented in Chapter 7). It assumes that these airlines will implement all the financially viable abatement options with new aircraft acquisitions financed at 2% per annum and repaid over 12 years and that the new aircraft acquired to handle the growth in passenger and cargo traffic in Chapter 6 are distributed between airlines that are currently servicing Australian international routes. This chapter recommends that additional study is needed to determine if using multiple CO_2 efficiency targets would improve the consistency of the offset obligations calculation for each airline.

Finally, Chapter 9 summarises how the thesis has met the overall research objectives and specific research questions and also highlights the strengths and limitations of the study. It demonstrates how the results of the thesis may: contribute to better awareness and knowledge in the areas of international aviation and aviation finance from the airlines perspective (bottom-up); serve to provoke future research; and ultimately how they may aid in the sustainable management of international airline emissions.

Chapter 2. Context

2.1 Aviation Industry

When a traveller is planning their next international flight they usually take into consideration the ticket price, airlines, time of departures, length of flights, frequent flyer programs, number of layovers, luggage allowance, airports to avoid to name but a few. Air travellers are beginning to think about their carbon footprint on their flights and are willing to pay to voluntarily offset their emissions (Choi & Ritchie, 2014; Lu & Shon, 2012). Some airlines such as Qantas and Virgin Australia have provided passengers the option to voluntarily offset their carbon emissions on their flights (Qantas, 2014; Virgin Australia, 2017). The amount of emissions on each flight is highly dependent on the aircraft used, aircraft total weight, route flown, weather conditions and congestion in the air and at the airport. The cost of fuel is a major component of the airlines business cost and when fuel cost was high, airlines purchased new efficient aircraft to reduce fuel use on each flight (Flottau, Broderick, Unnikrishnan, & Schofield, 2015; Townend, 2011). But when the price of oil dropped from over US$120 a barrel to less than $40 a barrel, airlines kept their less fuel efficient aircraft instead of retiring and renewing to more efficient aircraft (Freed, 2016; Mangla, 2015).

The airline-aviation industry is made up of multinational manufacturers, global network of suppliers, government and privately run airlines, airports, air navigation service providers, fuel providers, freight companies, caterers, travel agents, labour unions, financiers, trade associations, public groups and many more. Each can directly and indirectly affect the amount of emissions generated. These stakeholders will all have varying influence in setting and shaping the national, regional and international aviation policy. Many governments have relied on the airline-aviation industry for expert advice on formulating regulations and policies or in some case self-regulation.

2.2 Aviation Regulation

Many parts of the airline-aviation industry, unlike other industries are heavily regulated by local, national and regional governments (Backx, Carney, & Gedajlovic, 2002; Button & McDougall, 2006; Gillen, 2011). Around the world some national airlines, airports, air traffic management infrastructure and services are government owned, controlled and regulated. Some manufacturers receive tax incentives and subsidies (directly or indirectly) to help with the development of new commercial aircraft, and airlines receive government contracts to transport government personnel (Knorr, Bellmann, & Schomaker, 2012; Vasigh, Fleming, & Tacker, 2013). Government regulations and interventions have both facilitated and hinder the evolution of the airline-aviation industries (Button & McDougall, 2006; Gillen, 2011; Morrison & Winston, 1989).

Looking back to the beginning of commercial aviation, governments have played an active and important role in nurturing the aviation industry. In the USA, the Contract Air Mail Act (1925) and Air Commerce Act (1926) subsidized airmail based on weight. To meet these requirements, manufacturers produced aircraft that can carry more weight and fly faster so as to maximize profits (Smithsonian National Postal Museum, 2004; Vasigh et al., 2013). The Watre Act (1930) changed airmail weight based subsidies to distance; manufacturers responded by producing larger aircraft that can fly longer intercontinental distance with the extra space used to transport passengers (Smithsonian National Postal Museum, 2004; Vasigh et al., 2013). Other policies and government agencies can have direct and indirect effects on the design of the aircraft. For example the US Federal Aviation Authority (FAA) Aviation Noise Abatement Policy (1976, 2000) specifies the noise standards that future aircraft must meet. The US Environmental Protection Agency (EPA) Clean Air Act is a US federal law that controls air pollution. It also sets emission standards in motor vehicles and aircraft.

In the USA, Australia and other countries, governments have deregulated the airline industries (Morrison & Winston, 1989; Qantas, 2010). Qantas for example was privatized in 1993 (Qantas, 2010). The US Airline Deregulation Act (1978) removed control of fares, routes and market entry for new airlines (Smithsonian National Air and Space Museum, 2007) but many carriers around the world are still government owned, controlled, and even after privatisation most still receive favourable treatment from their governments as the national carrier. Airlines under financial difficulty have also being re-nationalized after privatisation (e.g. Air New Zealand in 2001) or seek government assistance (e.g. Qantas in 2014 lobbied the Australia federal government to review the Qantas sales act that limited foreign ownership of Qantas) (Griffiths, 2014; Kohler, 2001).

Airlines right to fly into and out of any cities of each country; number of carriers and number of flights are subject to negotiated bilateral agreements between each country. The first bilateral agreement was signed in Bermuda in 1946 between the United Kingdom (UK) and USA. This was updated in 1977 before it was superseded by the Open Skies agreement between the EU and USA in 2000. All other bilateral and multilateral agreements display similar properties to the Bermuda agreement. The first Open Sky agreement was signed between USA and the Netherlands in 1992; the agreement allows airlines from each country to fly any route with no limitations on the number of carriers or flights. Most bilateral, multilateral Air Service agreements and Open Skies agreements will specify all or a subset of the nine Freedoms that will be granted (Vasigh et al., 2013). As of

2017, Australia has treaty level Air Services Agreements accompanied by arrangements with 97 countries/economies (Bureau of Infrastructure Transport and Regional Economics (BITRE), 2017).

The UN ICAO was established in 1944 to “manage the administration and governance of the Convention on International Civil Aviation (Chicago Convention)” (ICAO, 2017). ICAO works with its Member States and industry groups on international civil aviation standards and recommended practices (SARPs) and policies (ICAO, 2017). Member States ensure that their local civil aviation operations and regulations adhere to these SARPs and polices. “ICAO also: coordinates assistance and capacity building for States in support of numerous aviation development objectives; produces global plans to coordinate multilateral strategic progress for safety and air navigation; monitors and reports on numerous air transport sector performance metrics; and audits States’ civil aviation oversight capabilities in the areas of safety and security” (ICAO, 2017).

2.3 Aviation finance and subsidies

Governments can provide funds or subsides for constructing airports, to develop new air routes, to upgrade production facilities, to research and develop new aircraft and aviation technology (Bednarek, 2016; Knorr et al., 2012; Ramos-Pérez, 2016; A. Smyth, Christodoulou, Dennis, Al-Azzawi, & Campbell, 2012). Governments can use their export credit agencies to greatly increase the number of new and more fuel efficient aircraft and additional capacity (seats) available. The Export-Import (EXIM) Bank of the US is the official export credit agency of the US federal government and it assists in financing the export of US goods and services to international markets (Ali, Hampson, Inglis, Sargeant, & Ali, 2013; Export-import Bank of the United States, 2012). The EXIM Bank provides credit and assumes the risk for countries that cannot obtain credit in the open market and it provides loan guarantees to certain foreign airlines to purchase Boeing aircraft. The three European export credit agencies – UK’s Export Credits Guarantee Department, Germany’s Euler Hermes and France’s Compagnie Française d'Assurance pour le Commerce Extérieur (Coface) perform a similar function to EXIM Bank in financing the sales of Airbus aircraft (Ali et al., 2013; International Airlines Group Legal Department, 2011).

2.4 Aviation emissions

All forms of aviation are responsible for about 2% of global anthropogenic CO_2 emissions and international aviation is responsible for around 1.3% of the global anthropogenic CO_2 emissions (ICAO, 2016b; IPCC, 2007).

Aircraft engines produce about 70% CO_2, about 30% water vapour (H_2O) and less than 1% is made up of black carbon (soot), sulphur oxides (SO_X), mono-nitrogen oxides (NO_X), hydrocarbons (HC), methane (CH_4) and carbon monoxide (CO) (U.S. Federal Aviation Administration (FAA), 2015). Soot is the second largest contributor to global warming after $CO_{2,}$ it absorbs heat and reduces albedo (Bond et al., 2013). Aircraft condensation trails (contrails) can cause cooling during the day and warming at night (Travis, Carleton, & Lauritsen, 2004). A multiplier of emitted CO_2 can be used to account for the effects from non-CO_2 emissions but at present there is no general agreement on the exact multiplicative factor to be used (D. S. Lee et al., 2009; Marbaix, Ferrone, & Matthews, 2008).

Shuttle buses, transport to and from airports, ground support vehicles and airport power (include power provide to aircraft at the gate) will generate similar emissions but this thesis will focus only on CO_2 emissions from aircraft, since CO_2 is the largest component of aircraft engine emissions.

2.5 Industry Commitments to CO_2 reduction

In 2008, members of International Air Transport Association that represent 240 airlines and 84% of total air traffic have committed to 1.5% fuel efficiency improvement per year to 2020, carbon neutral growth from 2020 and 50% net carbon emission reductions by 2050 relative to 2005 (Air Transport Action Group (ATAG), 2016; International Air Transport Association (IATA), 2009, 2013a). At the 38th session of ICAO Assembly in 2013, members endorsed the aspirational goal of global fuel efficiency improvement of 2% per annum and carbon neutral growth from 2020 (ICAO, 2013c). To achieve these goals, a number of emissions abatement measures including global MBM, alternative fuels, improvements in technology and operation will need to be adopted.

2.6 Emissions abatement options

In the airline-aviation industry, the four main categories of abatement options that are available for reducing CO_2 emissions are: (Banbury, Behrens, Bowell, et al., 2009; Banbury, Behrens, Browell, et al., 2009; Braathen et al., 2012; L. M. Dray, Evans, Reynolds, Schäfer, & Vera-Morales, 2009; Green et al., 2005; Holland et al., 2011; IPCC, 1999; Kar, Bennefoy, & Hansman, 2010; Morris, Rowbotham, Morrell, et al., 2009)

1. Improve the amount of fuel used by changing aircraft operations. This may include:
    a) Change aircraft flight path (improve air traffic management (ATM)) (Asia and Pacific Initiative to Reduce Emissions (ASPIRE), 2012; Grewe et al., 2014; Søvde et al., 2014).
    b) Improve airport infrastructure (National Research Council et al., 2011).

c) Increase aircraft load factor by combining flights and cancelling underutilised ones (Steven & Merklein, 2013).
d) Using larger aircraft on trips (Morrell, 2009).
e) Reduce aircraft weight e.g. Less drinking water and food, reduce packaging on food on short flights, light weight seats, carpets, inflight entertainment (IFE) equipment, galley equipment, cockpit equipment (Poll, 2014).
f) Lower aircraft cruise speed (Lovegren & Hansman, 2011).
g) Retire less efficient older aircraft (L. Dray, 2013).
h) Change maintenance intervals (L. M. Dray et al., 2009).

2. Develop and acquire aviation technology to reduce fuel used. This may include:
   a) Develop and acquire new fuel efficient aircraft technology (Graham, Hall, & Vera Morales, 2014):
      i) Develop and acquire new engines/engine technology such as Open rotor, hybrid electric propulsion, boundary layer ingesting.
      ii) Develop and acquire new fuel efficient aircraft including radical aircraft design such as blended/hybrid wing body, double bubble body (Hileman, De la Rosa Blanco, Bonnefoy, & Carter, 2013).
      iii) Use lightweight material in all parts of the aircraft from airframes to seats.
      iv) Develop and acquire wings with better lift to drag ratio.
   b) Improve current aircraft efficiency (Berglund, 2008):
      i) Reduce drag e.g. Winglets, Riblets, Laminar Nacelles, etc.
      ii) Reduce aircraft weight e.g. light weight seats, carpets, trolley, washing engines, washing aircraft, reduce paint.
      iii) Reduce the use of Auxiliary Power Unit while at airport.
3. Refuel with Alternative Fuels (Dillingham et al., 2014; Gegg, Budd, & Ison, 2015; Stratton, Wong, & Hileman, 2010).
4. Changing travellers' behaviour that could lead to less demand for air travel. This may include:
   a) Teleconference instead of business travel (Borggren, Moberg, Räsänen, & Finnveden, 2013; Davies & Armsworth, 2010).
   b) More efficient alternative transportation (Borken-Kleefeld, Fuglestvedt, & Berntsen, 2013).

Some abatement options such as installing winglets, retrofitting with lightweight cabin equipment, taxiing on one engine, washing aircraft engines, etc. can be implemented immediately but other abatement options such as acquiring the next generation of fuel efficient aircraft (like 737MAX, A320NEO, 777X) will have a longer lead time since these aircraft will enter service within the next 10 years (Airbus, 2016b; Bachman & Schlangenstein, 2017; Norris, 2013).

Not all of these abatement options can be actioned by airlines on their own; some can only be actioned by local, national or regional governments, manufacturers and other stakeholders in the airline-aviation industry. For example, local and/or national governments usually pay for improvements to airport infrastructure whereas national and/or regional governments pay for upgrades to ATM systems that in turn might require new equipment in aircraft and/or retraining of aircrew to make use of these improvements.

Future aviation technologies such as hybrid-electric propulsion, blended/hybrid wing-body, double bubble plane, etc. may come on the market in the next 20 to 40 years with up to 70% reduction in fuel consumption when compared to conventional (tube-and-wing) aircraft (Graham et al., 2014). Some of these future aviation technologies are still in small scale development phase and it’s highly unlikely that commercial companies will research these projects without government assistance (Graham et al., 2014). Apart from saving fuel, these future technologies must meet other requirements and regulations such as noise, emissions, scalability, and emergency evacuation and gate size before entering service.

2.7 Environmental policy instruments

There are a number of environmental policy instruments available to reduce CO_2 emissions in aviation. These instruments can encourage research, development and adoption of emission reduction technologies, improve efficiency and increase awareness. The list of environmental policy instruments may include taxes on emissions, tradable emissions permits, support for meeting emissions baselines, taxes on emissions intensive goods and services, support for green technologies, directly mandate the use of certain technologies, regulations, standards, financial incentives and voluntary agreements.

A number of these instruments, their main advantages and disadvantages are summarised in Table 2.1 (Burniaux et al., 2009; Cebreiro-Gómez et al., 2006; Duval, 2008; Goulder & Parry, 2008; Huppes & Simonis, 2009)

Table 2.1 Environmental policy instruments

Policy Instrument	Description	Pros and Cons
Emission tax.	A tax on emissions where the amount of tax paid is proportional to the quantity of emissions generated.	Since the abatement cost is equal to the tax, it makes it simple to administer and implement nationally or across a region but it also makes it easier to remove thus creating uncertainty. The emission tax provides a stable carbon price with less chance for corruption and revenue collected can be recycled. One of the main disadvantages is the cost and difficulty in monitoring and enforcement. Developing nations tend to have higher carbon intensity and will be impacted more by an emission tax and are less able to afford the cost of enforcement, monitoring and administration. Stakeholders and groups affected adversely by the emission tax will lobby against it. Emission tax does not limit the actual amount of emissions generated and could reduce competitiveness when compared to none taxed regions.
Tax on goods or services.	Tax emissions intensive goods and services such as products, fuel, air travel, electricity, etc.	Higher taxes can lead to less demand but does not encourage cleaner production of emissions intensive goods and services and does not focus on the externalities. It can be easier and cheaper to implement especially when emissions monitoring is difficult. Taxing emissions intensive goods and services reduce the competitive advantage of imports from non-taxed regions.
Subsidies for pollution abatement.	Policy instrument that rewards industries for every unit of emissions below a baseline emissions level.	Subsidies will lower cost only when emissions are below an artificial emissions baseline. It's not as cost effective as emission taxes or tradable emission permits. Provides the wrong production incentive.
Tradable emission permits.	Emission permits are similar to Emission Taxes where an emitter must have a permit for the amount of emissions produced.	The number of permits is capped and the permits are tradable. The permit price fluctuates depending on the market and can respond quicker than emission taxes but can also lead to carbon price volatility. Capping the number of permits can create an artificial upper bound on emissions. Nations and regions can setup separate emission permit trading scheme and can reduce permit

Policy Instrument	Description	Pros and Cons
		price volatility by linking different schemes together. Linked scheme can have an adverse effect on carbon price with regions and nations losing sovereignty over their local emission targets. If these national and regional schemes are not comparable then integration will be difficult. Setting up an emissions permit-trading scheme, monitoring, enforcement and paying for permits can be expensive and difficult especially for developing nations. Help can be provided to disadvantaged stakeholders and countries by allocating free permits (grandfathering). Lax monitoring can reduce permit price whereas a monopolistic permit seller can drive up the permit price and abatement cost. To tackle ‘local’ emissions, permits can be restricted by region or industry.
Technology support.	Instrument that support research, development and adoption of green/new technology. This can be direct funding, tax incentives, subsidies, intellectual property law, investor incentives, etc.	Policy instrument that support the research, development and adoption of green technology will mainly address future emissions and does not directly address the current demand, emissions and externalities. Technology subsidies will boost the economy but can create market distortions and it’s not the most cost effective way of encouraging research, development and adoption of new technology. It can be used to target specific technologies and adoption issues but can also target or support the wrong technologies. There is also no guarantee that the new technology will deliver the desired outcome with some having long and undefined lead times. Technology subsidies may require additional administration cost and does not tackle the whole chain and process. Technology support instruments are more effective when implemented in conjunction with market-based incentives. Technology support instruments spread the cost over the population but benefits only the researchers, developers and adopters of the green technology.

Policy Instrument	Description	Pros and Cons
Command and Control.	Direct regulatory type instrument can be used to mandate the use of certain technology, performance standard, eco labelling, public disclosure, etc.	Technology mandates affects only part of the production chain, reduce emitter's choice of abatement options and since all firms must comply regardless of individual situation it is unlikely to reduce abatement cost. Technology standards may be more cost effective when emission monitoring is difficult. Performance standards allow industry to pick and choose the appropriate means of meeting their commitments but do not control the emissions quantity. Standards can be monopolised by lobby groups and can gradually be undermined. Standards are difficult to determine if they are too weak or strong and there are no incentives to do more than what is required. Eco-labelling and public disclosures provide information to educate the consumer but only affect future emissions. Command and control instruments are easy to enforce and is more effective when implemented in conjunction with other instruments like MBM. Can have negative interactions with other policy instruments. Command and control instruments do not cope well with change since regulators may not have the most up to date information (when setting technology and performance standards). Unlike taxes and permits, cost is not as visible. Easier for consumers to understand.
Voluntary agreements	Voluntary Agreements between government and stakeholders on limiting emissions can be seen as a special type of Command and control instrument.	They can raise awareness, can be easier to implement and lead to stricter agreements. It's not cost effective since there are no incentives to do more than what is specified. Since it's voluntary, there are no guarantees that emissions are reduced or the cheapest abatement options are implemented. Voluntary Agreements can lead to or combine with the threat of more stringent policies. It can also be monopolised by lobby groups so as to avoid or even prevent stricter measures. Can be difficult to monitor, report or enforce.

2.8 Political Obstacles

In an ideal world, the policy instruments used to tackle GHG emissions will be the most cost efficient and environmentally effective, and at the same time produce the most benefits. But the policy instruments that are introduced are usually a compromise between what is effective, beneficial and feasible. Apart from the advantages and disadvantages listed in Table 2.1, each policy instrument has their own unique political and sometimes constitutional hurdles to overcome before becoming the law. In some countries and regions the cultural, social and standard practices may greatly influence the type of instruments that will be introduced and applied.

For example, the UK Labour Government introduced Climate Change Levy (CCL) as part of a number of policy instruments to reduce GHG emissions. The CCL is a tax on energy used, and the Labour Government had to make sure that the CCL did not unduly affect the poor, so as not to lose voter support (in coal mining areas) or cause energy price rises for households. The Labour Government also wanted to avoid to be seen as a high tax, big spending and anti-business government. The CCL taxed energy used by industry only but excluded the transportation sector and households, and encourages the use of renewable energy but not nuclear power. The transportation sector was excluded because they were subject to other MBM. CCL provided discounts for industries that reduce emissions to or over an agreed baseline but no incentives were given to electricity generators (D. Pearce, 2005).

In Canada, a mix of instruments was introduced at both the federal and provincial/territorial level to tackle regional NO_X and SO_X air pollution. The Canadian constitution states that each province or territory has responsibilities for environmental protection within their borders but the federal government address cross-border pollution and product standards such as vehicle and fuel standard. The Canadian federal government developed national standards with provincial/territorial governments who then use these standards to develop their own provincial/territorial regulations (OECD, 2007).

Cherry et al. (2014) showed that cultural and social factors can influence support for low-carbon technology (Cherry, García, Kallbekken, & Torvanger, 2014). They determined that an individual’s cultural worldviews greatly influence their support of publicly funded R&D whereas local economic interests influence their support of deployment of low carbon technology.

Finally the passage of environmental policy into law is not the end of the struggles as can be seen in Australia where the elected conservative government has dismantled the “carbon tax” laws that were passed by the previous Australian Labour government.

For each of policy instrument listed in the Table 2.1, Table 2.2 summarise some of these political obstacles from the perspective of the voters, politicians and affected industry (Burniaux et al., 2009; deSerres, Llewellyn, & Llewellyn, 2011; Hammar, Lofgren, & Sterner, 2004; Kirchgassner & Schneider, 2003; Oates & Portney, 2003).

Table 2.2 Policy Obstacles

Actors	Market Based Measures (E.g. Emissions Tax, Permit, Goods and Services Tax)	Command and Control (E.g. standards, regulations, etc.)	Technology Support (E.g. subsides, incentives, intellectual property etc.)	Voluntary Agreement
Politician	No votes for new taxes. Difficult to negotiate an equalised tax or standardised permit. Hard convincing voters that money collected will be used appropriately or recycled (into tax reductions, subsidies, or incentives).	Easier to sell to industry and voters. Not tackling the current emissions.	Tackling only future emissions (not current demand). Voters want more immediate benefits and actions. More government administration required. Government funding private industry.	No enforcement. Perceived as not doing enough.
Industry (+ their special interest groups)	Lobby against paying for emissions. Lobby for exceptions or grandfathering of permits (instead of auctions). Threats of staff reductions, industry shut downs or relocation due to additional cost.	Lobby for less restrictive regulations with minimal economic liability. Prefer Command and Control to MBM since there is no cost on current emissions.	Lobby for subsidies, tax incentives by affected industry. Lobby against if it's seen as helping competitors.	Non-binding. Lobby for voluntary agreement only if government threaten to implement traditional command control or taxation. Lobby for the least restrictive voluntary agreement.
Voter / Public	Not likely to vote or support another tax or revenue generator.	Bigger government to manage new regulations (bigger government seen as a waste of public	Concern about supporting the wrong technology. Bigger government	Non-binding. Perceived as not doing enough. Hard to enforce, if

Actors	Market Based Measures (E.g. Emissions Tax, Permit, Goods and Services Tax)	Command and Control (E.g. standards, regulations, etc.)	Technology Support (E.g. subsides, incentives, intellectual property etc.)	Voluntary Agreement
	Not convinced that taxes are used to solve the emissions problem or recycled. Need to be convinced to pay price now for the benefit of future generations. Believe that polluters not paying enough and non-participants are freeloading. Believe that industries will reduce wages or relocate to areas with no MBM. Perceived as extra burden or increase cost of living. See permits as licences to pollute. High consumers of a product or service affected by the tax or permit will vote against taxes/permits (and vice versa). Lobby for the other policies that are seen as "costing nothing" (on the surface).	funds by voters). Lose or bad regulations mean polluters not paying enough. Voters more interested in solutions to tackle current emissions but Command and control instruments tackle future emissions. Voters directly impacted by emissions will want more strict standards.	to administer funds. Benefits are too far in the distances. Government funding/support private industry. Voters directly impacted will want more (technology) support but other voters will view it as government welfare to industry.	no penalty.

2.9 Policy Interaction

Since most environmental problems are more than just reducing the total amount of GHG emission, environmental policies will contain more than one instrument which could target one or more stakeholders (industries, sectors, etc.), address multiple market behaviours or issues. This mix of instruments can directly and/or indirectly affect the same/different stakeholders, market behaviours or issues both positively and negatively (Goulder & Parry, 2008; OECD, 2007; Sorrell & Sijm, 2003).

For example, a policy with both an emission tax and an emission permit instrument where emitters can choose how they meet their commitments can reduce their cost uncertainty but may reduce the effectiveness of emission tax (OECD, 2007).

OECD reviewed a mix of instruments from around the world that tackled household waste generation, water pollution, mercury emissions, regional air pollution and residential energy efficiency, and in the residential energy efficiency example, a mix of energy tax, financial support, performance and technical standards, information based instrument like energy labels and voluntary instrument like appliance efficiency were used in Canada and the UK to not only reduce energy consumption but to improve energy efficiency (OECD, 2007).

Lyon et al. (2003) presented a gaming model that determines the environmental technology adoption under unilateral action, voluntary agreements and taxation (Lyon & Maxwell, 2003). The model showed weak voluntary agreements are often used when stronger policy instrument (such as taxes) are not political feasible due to heavy lobbying and resistance from the affected industries. The model showed that inefficient companies affected by taxation could either leave the industry or adopt cleaner technology, whereas voluntary agreements will cause companies to do only the latter. Companies that adopt voluntary agreements will also increase lobbying against tax proposals but some may choose to adopt unilateral action to pre-empt taxation (Lyon & Maxwell, 2003).

Environmental policies can interact with policies in other areas, Sijm (2005) concluded that the national energy policies in sectors that are also participating in the European Union Emissions Trading System (EU-ETS) should be abolished since it would make the CO_2 performance of EU-ETS less optimal having overlapping policy instruments. Sijm (2005) states that overlapping policies can only be justified if it improves the design and political acceptability of EU-ETS, reduce (technology, market) barriers, correct market failures and/or meet other objectives.

An optimal policy need to be cost effective at reducing emissions, encourages research and development (R&D), promotes learning from producing and adopting new technology, and cope with market/emission fluctuations (Duval, 2008; Fischer & Newell, 2008). Duval (2008) recommends selecting some form of price instrument (such as tax or emission permit) in combination with technology support, standards and/or voluntary agreements. Fischer and Newell (2008) evaluated six policies used in the electricity sector for reducing GHG emissions and concluded that a mix of policy instruments that includes an emission price, subsidies for R&D and learning is more cost and environmental effective than any single instrument alone (Fischer & Newell, 2008). These six policies were pricing CO_2 emissions, tax on fossil fuelled energy, tradable emissions performance standard, portfolio standards of renewables, production subsidy for renewables and subsidies for R&D.

There is also a belief that imposing a price on CO_2 emissions will lead to more R&D in environmentally friendly technology. Gans (2012) determined that this assumption is not necessarily true. Gans's model shows that higher carbon price leads to less fossil fuel usage and may improve the R&D of alternative or non-emitting technologies but may discourage R&D into more fuel efficiency technology (Gans, 2012).

In Hamamoto's analysis of household CO_2 emissions, policies that include high carbon price and economic incentives are not enough to change household behaviour but suggest including cooperative policies that "influence psychological factors" such as feedback and reward, information, etc. (Hamamoto, 2013).

In Asia, the main factors that are causing the growth of CO_2 emissions in the transport sector are economic and population growth and some Asian countries are applying a mix of policy instruments such as fuel efficiency standards, occupancy rates, eliminate or reduced fuel subsidies, tax incentives, fuel switching, congestion pricing to curb CO_2 emissions (Timilsina & Shrestha, 2009).

According to Hofer et al. an air travel carbon tax on US domestic routes will increase airfares and may discourage some travellers from flying. Traveller may switch to automobile travel on shorter routes, thus leading to higher automobile emissions and lower total air travel emission savings (Hofer, Dresner, & Windle, 2010).

Looking at these examples from other industries, sectors, and regions it is clear that a portfolio of instruments is required to achieve the CO_2 emissions reduction objectives. In producing an environmentally effective and economically efficient mix of environmental policy instruments, OECD (2007) listed three main criteria that should be met:

1) Cost versus benefit, i.e. cost of implementing the instrument mix versus the benefits
2) Cost-effectiveness, i.e. cost of applying the instrument mix

3) Environmental effectiveness, i.e. environmental benefits of instrument mix

2.10 Aviation and EU-ETS

The inclusion of international flights to and from the European Union (EU) in the EU Emissions Trading System (ETS) was the first major attempt to regulate international aviation emissions. To meet its Kyoto commitments, the EU introduced an Emissions Trading System in 2005 to reduce GHG. The EU-ETS placed an absolute limit on the quantity of emissions emitted and businesses require emission allowances before emitting. Most businesses are allocated some free allowances with the others auctioned. Businesses that can keep their emissions below their allowances can sell their extra allowances and those that cannot keep their emissions below the free allowance can invest in low/clean emissions technology and/or purchase additional allowances on the open market. Businesses that do not have enough emission allowances to cover their emissions will be fined. Aviation was included into the EU-ETS where airlines had their 2012 emissions capped at 97% of the average annual emissions in 2004 to 2006 and their emissions cap for 2013 to 2020 reduced to 95%. 85% of emission allowances are issued for free and the other 15% will be auctioned off. Only flights arriving at or leaving from EU airports are included in the EU-ETS, this includes flights that originated from or destined to airports outside the EU (McConnachie, 2012).

By setting a price on emissions, it was hoped that as the price of emission allowances goes up business would invest in lower emission options. The global financial crisis and subsequent economic downturn has caused businesses to emit less. Fewer emissions mean there was less need for emission allowances, which then drove down the price of emission allowances. A lower cost for emission allowances reduced the incentive for investing in cleaner emission technologies. Some options considered include propping up the price of emission allowances by setting a price floor, auctioning less allowances and having allowances that take into consideration economic and emission forecasts (van Renssen, 2012). During the economic downturn airlines restructured, merged, reduced frequency of flights, shrunk their network, used smaller aircraft, flew more efficient aircraft, parked their unneeded/less efficient aircraft in the desert or simply went bankrupt or out of business (Clark, 2010).

Since the EU-ETS is not part of a global emissions market scheme, indirect flights between non EU countries that use an EU hub will incur additional costs and indirect flights between EU and non EU country could incur lower costs if the transfer takes place in a non EU country. Certain indirect routes can cause carbon leakage if avoiding EU-ETS increases travel to non EU countries on less emissions efficient flights or modes of transport (Bognár, 2012). The solution is to have a global aviation emissions market scheme where all international flights are included; this will stop aircraft operators from using “pollution havens”.

At least twenty-six (26) non-EU countries opposed the inclusion of international flights in the EU-ETS and several North American airlines challenged the inclusion of non-EU owned airlines in the EU-ETS in court. The European Court of Justice has ruled that EU’s legislation on aviation emission is valid under international law, but the EU has decided to apply EU-ETS only on flights that depart from and arrive at EU airports (European Union Court of Justice, 2011). Because European airlines were included in the EU-ETS, they were forced to improve their efficiency, which resulted in a higher average efficiency than non-European airlines (Li, Wang, & Cui, 2016).

2.11 ICAO’s Market-Based Measure

At the 38th ICAO General Assembly in 2013, members defined a “basket” of measures to achieve the ICAO’s global aspirational goals of carbon neutral growth and 2% fuel efficiency improvements from 2020 (ICAO, 2013a). These measures will include implementing fuel saving technologies, improving aircraft operation, refuelling with sustainable alternative fuels but it will not be enough to achieve carbon neutral growth after 2020 (International Air Transport Association (IATA), 2009). At the 38th Assembly, members agreed that to meet these commitments some form of MBM will need to be developed and presented at the 39th session with the goal of implementing the MBM scheme from 2020 (ICAO, 2013a, 2013c).

At the 39th ICAO General Assembly in 2016, a global MBM in the form of a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was presented (ICAO, 2016d). The voluntary pilot and first phases of the CORSIA will begin in 2021 and end in 2026, while the second phase will run from 2027 to 2035 (ICAO, 2016d). As of October 2016, 66 states have volunteered to participate in the CORSIA from 2021 and in phase 2; states whose share of international aviation activity in Revenue Tonne Kilometre (RTK) in 2018 is ½% of the total RTK or whose cumulative share is 90% of the total RTKs will be included. Least Developed Countries, Small Island Developing States and Landlocked Developing Countries will be excluded but can volunteer to participate in phase 2 (ICAO, 2016d). From 2021, the CORSIA will cover routes between participating states and allocate offset obligations to aircraft operators on these routes based on a combination of the global average growth factor and individual operator’s growth factor in emissions in each year. From 2021 to 2029, only the global growth rate factor will be used before switching to a combination of global and individual growth factor from 2030 (ICAO, 2016d). Aircraft operators can fulfil their offset obligations by obtaining and redeeming emission units generated outside the international aviation sector. These will include emissions units from

UNFCCC Clean Development Mechanism (CDM), Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) and eligible emissions units purchased from the carbon market.

Chapter 3. Methodology

3.1 Research Objectives

This thesis seeks to achieve the following research objectives:

- Determine the carbon emissions profile of airlines flying on international routes into and out of Australia and determine how the main drivers such as flight distance, aircraft type and payload (i.e. passengers and freight) has on each airline's emissions profile.
- Determine the impact of low-interest loans on the uptake of emissions abatement options and the change in the emissions profile for these airlines over time.
- Finally, determine a pathway forward to not only mitigate the growth in emissions, but also to improve efficiency while giving airlines the freedom to choose from the ICAO's basket of emissions abatement measures.

3.2 Research Questions

This thesis will achieve these objectives by answering the following three research questions:

Research Question 1.	What is the CO_2 emissions profile of airlines operating in the Australian international routes?
Research Question 2.	What emissions abatement options are available to airlines on Australian international routes and what is the impact on the future CO_2 emissions profile? What are the marginal abatement costs and what is the impact of low-interest finance?
Research Question 3.	What integrative policies could facilitate more effective emissions outcomes on the Australian international routes?

3.3 Methodology overview

Investigating these research objectives involved three broad methodological stages, as highlighted in Figure 3.1 and as discussed below.

Note: A detailed methodology for each stage is presented in Chapters 4 to 7.

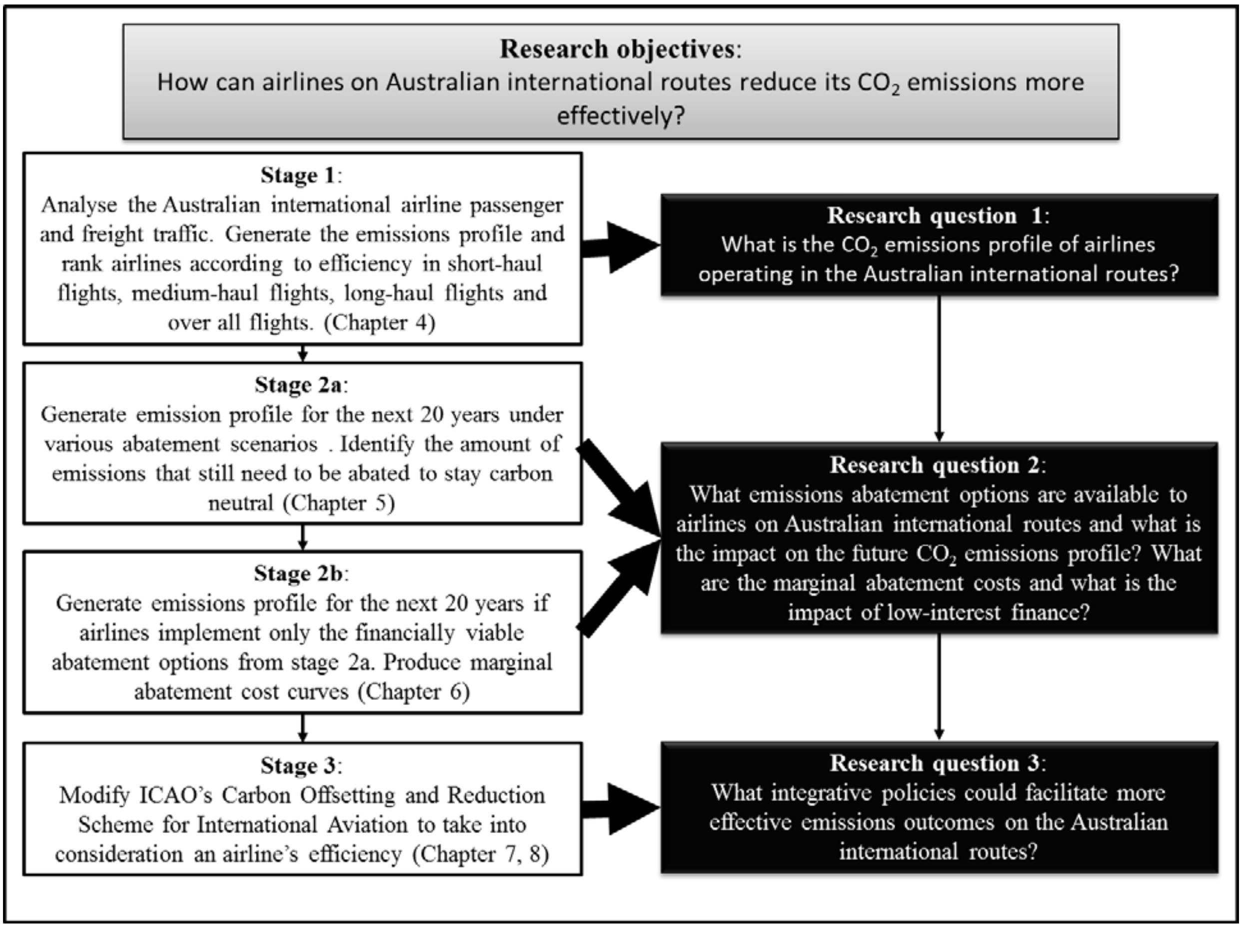


Figure 3.1 Methodology Overview

3.3.1 Stage 1

Stage 1 (results in Chapter 4 and Yin et al. (2015)) determines the CO_2 emissions profile of airlines flying international passengers and freight (including mail) into and out of Australia in 2012. In this stage, only passengers and freight traffic along some of the most populous Australian international routes are included. The CO_2 emissions model used to determine the CO_2 emissions profile is based on the ICAO carbon emissions calculator which assumes that aircraft will fly the great circle path between each airport. The Australian Government's Bureau of Infrastructure, Transport and Regional Economic (BITRE) collected the passenger and freight traffic data that was used in the model. The airline flight schedules database for 2012 was purchased from Innovata. The flight schedules contain not only airline, origin and destination location, but also the number of flights and seats on each aircraft type used on the route. The amounts of fuel that each aircraft type consumes are published by the European Environmental Agency (EEA). The CO_2 emissions profile for each airline is composed of the total amount of CO_2 emitted and CO_2 efficiency. An airline's emissions profile for short-haul flights, medium-haul flights, long-haul flights and all flights were produced. Post-processing of the CO_2 emissions profile is performed in Microsoft (MS) Excel.

In summary, this stage answered research question 1 by producing CO_2 emissions profile (i.e. CO_2 emitted and CO_2 efficiency) of airlines flying on some of the most populous Australian international routes.

3.3.2 Stage 2a

Stage 2a (results in Chapter 5 and Yin et al. (2016)) builds on Stage 1. Starting from 2013, and over the next 20 years, passenger and freight traffic are predicted to grow at the annual rates of 6% and 5%, respectively. A number of abatement options were identified and incorporated into the emissions model from Stage 1 to determine the change in the CO_2 emissions profile over the next 20 years. These abatement options range from increasing the load factor, reducing the number of engines used while taxiing to and from runway, reducing the weight of current fleet, installing winglets to improve aerodynamics, acquiring new aircraft to handle the traffic growth and renewing the current fleet. A business-as-usual and four abatement scenarios were simulated. Each abatement scenario combines a number of abatement options to determine the maximum emissions reduction and to identify the amount of emissions that still needs to be abated in order to achieve carbon neutral growth from 2020. The first abatement scenario combines retrofitting the current fleet with emission-reducing technologies, changing airline operations and acquiring new aircraft to handle the growth in passenger and freight traffic. The second abatement scenario builds on the first, but with all routes currently serviced by Boeing 747s being replaced with new aircraft. The third abatement scenario focuses on acquiring the latest aircraft to renew the current fleet and to handle the growth in passenger and freight traffic. In the third abatement scenario, airline operations are not updated and no current aircraft are retrofitted with emission-reducing technologies. In the fourth abatement scenario, the total numbers of additional flights are reduced by “packing” more passengers on each flight. The passenger load factor on each flight in the three previous abatement scenarios are increase by 5% and 10%.

3.3.3 Stage 2b

Stage 2b (results are in Chapter 6) builds on Stage 2a. As passenger and freight traffic increase over the next 20 years, the change in CO_2 emissions profile will depend on the abatement options that airlines implement. This stage will model airlines that implement only financially viable abatement options (i.e. abatement options with negative or zero marginal abatement cost). The abatement cost for implementing some of these abatement options can be found on manufacturers’ web-sites but most were estimated based on data and information published in aviation trade journals and adjusted for inflation over the next 20 years. Apart from aircraft acquisition, all other abatement cost are not discounted or financed. Due to the high cost of acquiring new aircraft, the model assumes that airlines will finance their aircraft purchases with interest rates of between 2% to 8% per annum repaid over 12 and 15 years. The model assumes that the actual price of the new aircraft are discounted by up to 50% of the listed price and depreciated over 25 years with a 10% residual value that is recouped when the aircraft is sold. If an aircraft type is no longer in production, airlines can acquire the use of these aircraft through leasing. The leasing model assumes a lease period of 5 years, with lease rates recalculated at the end of each lease period. Aircraft maintenance cost are also included in the costing model and are adjusted depending on the age of the aircraft. The results in Stage 2a are post-processed in MS Excel to incorporate the abatement cost model and MACCs are generated. Because interest rates and repayment periods are varied, the emissions profile presented in Stage 2a are also recalculated to include only the financially viable abatement options and to identify the amount emissions that still needs to be abated in order to achieve carbon neutral growth from 2020.

In summary, Stages 2a and 2b answered research question 2 by determining the CO_2 emissions profile over the next 20 years after implementing the most financially viable abatement options.

3.3.4 Stage 3

Stage 3 (results are in Chapter 7 and Chapter 8) builds on the lessons learnt from the previous two stages. In Stage 1, airlines on the Australian international routes were ranked according to the amount of CO_2 emission generated and CO_2 efficiency. Stage 2b shows that, even after implementing a number of financially viable abatement options, additional emissions still need to be abated in order to stay carbon neutral after 2020. At the 39th ICAO Assembly, a phased implementation of a global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was presented. The CORSIA allocates carbon offset obligations to each airline based on the amount of emissions than each airline generated. In Stage 3, this formula will be modified so that carbon offset obligations will also take into consideration each airline's relative success or failure at meeting the CO_2 efficiency target. In Chapter 7, a simple example will be used to illustrate the changes to carbon offset obligations under this new scheme and shows how the new scheme provides additional incentives for each airline to be more efficient.

Assuming airlines servicing the Australian international routes implement all their financially viable abatement options and airlines finance their new aircraft acquisition at 2% per annum over 12 years, carbon offset obligations from 2021 are calculated using ICAO's CORSIA and the improved carbon offset scheme presented in Chapter 7. The initial CO_2 efficiency target in 2021 is the average CO_2 efficiency from 2019 and 2020 and, because ICAO has committed to a global fuel efficiency improvement of 2% per annum, each subsequent CO_2 efficiency target is set at 2% lower than the previous year. The carbon offset obligations for airlines servicing Australian international routes under the CORSIA and the new scheme starting from 2021 are presented in Chapter 8.

In summary, Stage 2b and 3 answered research question 3 by showing how policy makers can use a combination of financial and performance standards (CO_2 efficiency target) to achieve better emission outcomes in international aviation.

Chapter 4. An analysis of the greenhouse gas emissions profile of airlines flying the Australian international market

Yin, K.-s., Dargusch, P., & Halog, A. (2015). An analysis of the greenhouse gas emissions profile of airlines flying the Australian international market. *Journal of Air Transport Management, 47*, 218-229.

Chapter Summary

In this chapter, 2012 data on airlines' aircraft characteristics, passenger load and cargo load (obtained from statistics reported by Australian Government Bureau of Infrastructure, Transport and Regional Economics) was used to estimate the volume and carbon efficiency on each international route flying to and from Australia. This is the first study to use actual passenger and cargo load data to determine the greenhouse gas (specifically CO_2) efficiency of airlines operating in the Australian international aviation market. Airlines' CO_2 emission profile is dependent on many factors including but not limited to the aircraft used, payload, route taken, weather conditions. The results reveal that the airlines' CO_2 emission profile is not only dependent on the aircraft used and the number of passengers but also the amount of cargo on each flight.

4.1 Introduction

Aviation accounts for 2% of the total global greenhouse gas (GHG) emissions according to the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) (Barker et al., 2007; IPCC, 1999). Over the next two decades passenger traffic and air cargo is expected to increase at a rate of 4.5% to 5.0% per year (Airbus, 2014b; Boeing, 2014b; Ribeiro et al., 2007) with GHG emissions growing at between 3-4% per year (Barker et al., 2007; ICAO, 2010). B. Owen, Lee, and Lim (2010) modelled the global aviation carbon dioxide (CO_2) emissions under the four Intergovernmental Panel on Climate Change/Special Report on Emission Scenarios (IPCC/SRES) plus one additional mitigation scenario and predicted that aviation CO_2 will grow to between 2.4% and 4.1% of the projected 2050 global CO_2 emissions

Unlike other industries, international flights generate emissions across many countries and legal jurisdictions, with the effects both visible (e.g. con trails) and invisible (e.g. carbon dioxide (CO_2), mono-nitrogen oxides (NO_X)). Only flights within New Zealand and the European Union (EU) are subject to some form of GHG emissions regulation (Braathen et al., 2012). International aviation emissions were not included in the Kyoto protocol (United Nations (UN), 1998). Article 2.2 directed The Parties in Annex I of the protocol to work through International Civil Aviation

Organisation (ICAO) in limiting and reducing GHG emissions. At the 2013 38th session of the ICAO Assembly, members agreed to develop and present recommendations on a global Market Based Measure (MBM) scheme for reducing international aviation GHG emission at the 39th session in 2016, with the goal of implementing MBM scheme from 2020 (ICAO, 2013a). The MBM is likely to also include alternative fuels, and improvements in technology and operations. Currently international aviation outside of the EU is not subject to any form of GHG emissions regulations. Aircraft emissions are not only made up of CO_2 but also black carbon (soot), sulphur oxides (SO_X), water vapour and NOX. To account for the effects of non-CO_2 emissions, a multiplier of emitted CO_2 such as Radiative Forcing Index (RFI), Global Warming Potential (GWP), and Global Temperature Potential (GTP) is used. Marbaix et al. (2008) recommended using a GWP-based multiplier of between 1.5 and 4.1 with a best estimate of 2.4, which includes the effects of NOX, contrails and induced cirrus clouds. D. S. Lee et al. (2009) suggested using 3.5% of total anthropogenic forcing (4.9% anthropogenic forcing including non-CO_2 and cirrus cloud) in 2005. Some airlines and many companies have produced aviation carbon emission calculators that allow individuals and businesses to offset their carbon emissions from air travel (Carbon Footprint, 2014; Carbon Neutral, 2014; Kling & Hough, 2011; myClimate, 2014; Qantas, 2014). These calculators use different methodologies and produce different estimates of GHG emissions equivalent (CO2e) for the same flight (Table 4.1). There is currently no consensus on which multiplier to use or how to include non-CO_2 aviation emissions. ICAO recommends focusing only on CO_2 aviation emissions since it is the largest component (ICAO, 2008).

Table 4.1 GHG Emissions (CO_2e) estimates using four different carbon calculators.

Trip (one way)	myClimate[1] tCO_2e	Qantas[2] tCO_2e	Carbon Footprint[3] tCO_2e	Carbon Neutral[4] tCO_2e
Sydney-Los Angeles (SYD-LAX)	2.373	1.616	0.96	2.18
Brisbane-Los Angeles (BNE-LAX)	2.256	0.955	0.92	2.08
Sydney-Abu Dhabi (SYD-AUH)	2.379	1.561	0.96	2.18
Sydney-Auckland (SYD-AKL)	0.430	0.114	0.18	0.44
Perth-Kuala Lumpur (PER-KUL)	0.782	NA	0.33	0.75
Sydney-Hong Kong (SYD-HKG)	1.379	0.818	0.59	1.33

The right to fly between an airlines' home country and any city of a foreign country or region (like the EU) is subject to negotiated bilateral or multilateral air service agreements. Most bilateral and multilateral Air Service agreements and Open Skies agreements will specify all or a subset of the nine Freedoms that will be granted (ICAO, 2013b; Vasigh et al., 2013). Prior to developing policies (such as economic, emissions and/or command and control policies) to manage and reduce CO_2 emissions from international aviation, policy makers in each country need to assess the amount of CO_2 emitted and the efficiency of all airlines on their international routes using actual load factors, flight schedule and aircraft characteristics.

Flight emissions calculators developed by various groups - ICAO (2014b); Jardine (2009); Kling and Hough (2010); C. Miyoshi and Mason (2009) - all follow similar methodologies and estimate the amount of CO_2 apportioned to a passenger based on the seat class, aircraft type, distance flown, average load factor on the route and may include the average cargo load on the route. The carbon calculator presented in C. Miyoshi and Mason (2009) used the actual airlines routes, load factor, aircraft type and cabin configuration but not cargo to highlight each airline's CO_2 emission performance in the UK market. In this thesis a modified version of the ICAO (2014b) Carbon Calculator Methodology was used to determine the CO_2 emissions profile of airlines that fly the Australian International aviation market using the airline's aircraft type, passenger and cargo load in 2012. For benchmarking to be effective, ICAO recommends that benchmarking (performance)

[1] (myClimate, 2014)
2 (Qantas, 2014)
3 (Carbon Footprint, 2014)
4 (Carbon Neutral, 2014)

parameters should be independent of different airline business model (ICAO, 2008). The CO_2 calculator developed in this thesis does not take into account the seat class that is usually attributed to the different airline business models (i.e. low cost, traditional network). The results demonstrate that an airline's choice of aircraft; seat density (i.e. number of seats in each aircraft), passenger load factor (i.e. % of occupied seats) and the amount of cargo transported on each flight can affect the CO_2 efficiency on Australian international routes.

4.2 Methods

The CO_2 estimates presented in this chapter were derived using the CO_2 Profile Calculator shown in Figure 4.1. This CO_2 Profile Calculator is a modified version of the ICAO Carbon Calculator Methodology that calculates the amount of CO_2 emitted on each flight (ICAO, 2014b). Unlike the ICAO Carbon Calculator, the algorithm used in this thesis does not take into consideration the class of travel. The calculator used in this thesis determines the amount of CO_2 emitted for an aircraft flying the great circle distance route between two cities. Passengers are treated as weighted payload and combined with the weight of freight (including mail) to form the total payload on each flight. The amount of CO_2 emitted is then apportioned to each kilogram of payload kilometre flown.

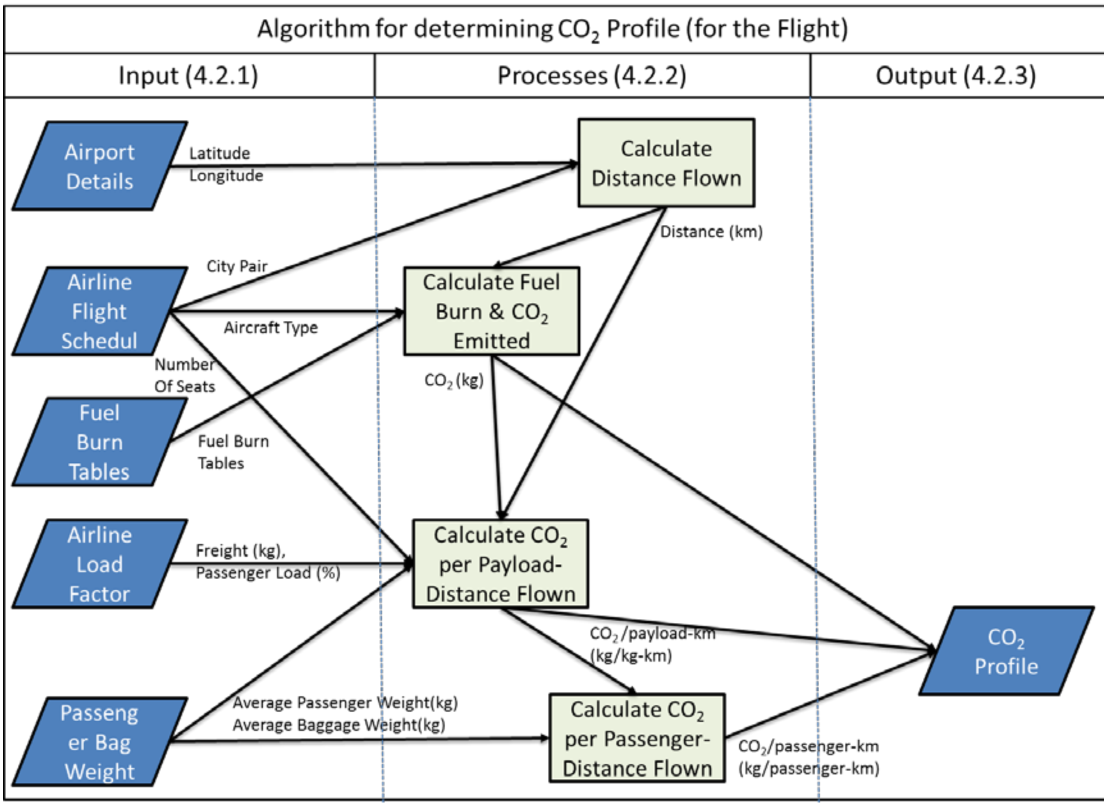


Figure 4.1 CO_2 Profile Calculator.

4.2.1 Input

4.2.1.1 Airport Details

Airport Details contains each airport's geographic location in latitude and longitude plus the three-letters International Air Transport Association (IATA) airport code, city, country name of the airport that each airline is flying to and from. This information was used to convert the airport/city pairs in the Airline Flight Schedule to geographic locations in latitude and longitude.

4.2.1.2 Airline Flight Schedule

Airline Flight Schedule contains the departure airport, arrival airport, aircraft equipment used, number of flights per month and the number of seats on the flight. This information can be obtained from each airline or purchased from companies that sell aviation information and analysis services (e.g. Innovata (2014); Official Airline Guide (OAG) (2014)).

4.2.1.3 Fuel Burn Tables

Fuel Burn Tables map the amount of fuel used by each aircraft type to fly a given distance. Most airlines have more detailed information on the fuel burn for each aircraft in their fleet but this information is not publicly available. In the algorithm used in this thesis, Core Inventory of Air Emission (CORINAIR) fuel burn tables are used to determine the fuel burnt on each flight (European Environment Agency, 2006). The fuel burn table maps the fuel used for each phase of the flight namely; taxi out, take off, climb out, climb/cruise/descent, landing approach and taxi in. Horton (2010) recommend using the CORINAIR fuel burn tables but with a few modifications listed in Table 4.2. These modifications improve the accuracy and create new fuel burn tables for newer aircraft like the 777-300ER and A380. For each fuel burn table, a quadratic function is also used to extrapolate and create additional table entries at intervals of 500nm (Supplementary data Table 4.10 to Table 4.13).

Table 4.2 Fuel Burn Table Modifications.

Aircraft Type	Modifications
A320	Raise the original A320 fuel burn in CORINAIR tables by 4.2%
A321	Increase the new A320 fuel burn by another 15.8%
737-800/900	Use the new A320 fuel burn numbers
737-700	Use 737-400 fuel burn minus 5%
767	Raise original 767 fuel burn by 7%
777-300ER /200LR	Raise original 777 fuel burn by 12%
A340-600/500	Raise the A340 fuel burn by 36%
A380	Use 747-400 but raise fuel burn by 15.5%

4.2.1.4 Airline Load Factor

The airlines will have more detailed information on their passenger load factor and the amount of cargo carried on each flight. This commercial in confidence information is not available to the public but some Government departments and/or airports record the number of passengers, load factor and/or cargo on all flights leaving and entering the country

4.2.1.5 Passenger and Baggage Weight

The average baggage and passenger weight can be dependent on passenger gender (i.e. male/female), travel season (i.e. summer/winter), aircraft type (i.e. commuter, narrow body, wide body), flight time, distance and airline business model (i.e. low cost, traditional network). International checked baggage allowance varies depending on where the airlines are flying to, e.g. flights to North America usually have higher checked baggage allowance than to South East Asia or New Zealand. Berdowski et al. (2009) surveyed 22,901 passengers and concluded that the average passenger weight should be set at 88kg with baggage weight of 17kg for a total average passenger mass of 105kg. The U.S. Federal Aviation Administration (FAA) (2005) recommends using a passenger weight of 190-195lbs (i.e. 86.1-88.5 kg) with at least 30lbs (i.e. 13.6kg) for checked baggage. According to ICAO (2009), 82% of airlines agreed that the average passenger mass (i.e. passenger plus baggage) should be 100kg with a few airlines recommending values between 95-105kg. About 70% of carriers suggest using an average checked baggage weight of 10-20kg for short haul international flights and 46% suggest using 20-30kg for long haul international flights. If no other values are available, ICAO (2013b) recommend using a passenger mass of 100kg.

4.2.2 Processes

4.2.2.1 Calculate Distance Flown

The actual flight path taken by airlines is not usually the shortest most direct route between two airports i.e. great circle paths. The aircraft might have to fly over or around bad weather, avoid war zones, circle around due to congestion, and take a longer route to take advantage of favourable wind conditions. In the algorithm used in this thesis, aircraft are assumed to fly great circle distance (GCD) between departure airport and arrival airport. To take into account of traffic congestion, weather and stacking 50km is added to the distance flown if the GCD is less that 550km, 125km if GCD is greater than 5500m and 100km for GCD between 550km and 5500km (ICAO, 2014b).

4.2.2.2 Calculate Fuel Burn and CO_2 emitted

Since the CORINAIR fuel burn tables are given in intervals of 500nm (i.e. 926km), intermediate values are interpolated using a (4^{th} order) spline to produce the amount of fuel burnt for distance flown. Even though airlines configure identical aircraft with different number of seats, the actual amount of fuel used when flying the same route will be similar since the variation in payload weight is small when compared to the aircraft operating empty weight (OEW). It was deemed unnecessary in the algorithm used in this thesis to recompute the fuel burn for different number of passenger and freight loads i.e. different payload. According to the ICAO Carbon Calculator methodology 3.157kg of CO_2 is emitted for each kg of aviation fuel burnt (ICAO, 2014b).

4.2.2.3 Calculate CO_2 per Payload-Distance Flown

This function calculates the amount of CO_2 emitted (in grams) for each kilogram of payload and kilometre distance flown. Payload of an aircraft is made up of the total weight of freight and passenger mass on the flight. Average passenger mass is the combined weight of an average passenger and checked baggage.

$$Aircraft\ Payload\ (in\ kg) = Num\ of\ Passengers\ \times Average\ Passenger\ Mass + Cargo\ weight$$

$$CO_2\ per\ payload\ distance = \frac{Fuel\ Burn\ (in\ g) \times 3.157}{Aircraft\ Payload\ (in\ kg) \times Distance\ flown\ (in\ km)}$$

4.2.2.4 Calculate CO_2 per Passenger-Distance Flown

Given the average passenger mass, CO_2 emitted per passenger kilometre flown can be estimated by:

$$CO_2\ per\ passenger\ distance = CO_2\ per\ payload\ distance \times Average\ Passenger\ Mass$$

4.2.3 CO_2 Profile

An airline's CO_2 profile on each route is made up of the quantity of CO_2 emitted, CO_2 per Payload-Distance flown and CO_2 per Passenger-Distance flown.

4.3 Calculations

4.3.1 Data input

The International Airline Activity data that was collected by the Australian Government's Bureau of Infrastructure, Transport and Regional Economics (BITRE) showed that the country where the largest source of international passengers in 2012 was New Zealand (NZL) followed by Singapore (SGP), United States of America (USA), United Arab Emirates (UAE), Hong Kong (HKG), Indonesia (IDN) and Malaysia (MYS) (Bureau of Infrastructure Transport and Regional Economics (BITRE), 2014). These seven countries account for 72% of the 29.6 million international passengers. Large number of passengers to and from a particular country can equate to large number of flights on smaller aircraft or large wide body aircraft that are usually used on longer routes. Rounding out the top 10 sources of passengers in 2012 are Thailand (THA), China (CHN) and Japan (JPN) with passengers to/from Thailand and Japan decreasing from 2008 to 2012. It is anticipated that passengers travelling to/from China will continue to increase and China-based airlines will play a more prominent role in Australian international flights in the future. This chapter will focus on routes between Australia and the top seven most travelled to countries. Passengers that arrived in Australia after a layover in an intermediate city (country) are deemed as passengers from the intermediate city (country) for the purpose of this thesis and not from the city where they started their journey (e.g. passengers travelling to/from London with a layover in Dubai or Singapore are treated as passengers to/from Dubai or Singapore). (Table 4.3)

Table 4.3 Source of the most Australia international passengers.

Year	Top 10 Sources of the most Australia International Passengers									
	1	2	3	4	5	6	7	8	9	10
2012	NZL	SGP	USA	UAE	HKG	IDN	MYS	THA	CHN	JPN
2011	NZL	SGP	USA	HKG	IDN	MYS	UAE	THA	CHN	FIJ
2010	NZL	SGP	USA	HKG	MYS	UAE	IDN	THA	JPN	CHN
2009	NZL	SGP	HKG	USA	UAE	MYS	THA	IDN	JPN	GBR
2008	NZL	SGP	HKG	USA	THA	UAE	JPN	MYS	IDN	GBR

In 2012, Qantas (QF) transported the most international passengers to and from Australia followed by Singapore Airlines (SQ), Emirates (EK), Virgin Australia Airlines (VA), Jetstar Airways (JQ), Air New Zealand (NZ), Cathay Pacific (CX) and Malaysia Airlines (MH) (Table 4.4). Rounding out the top 10 are Thai Airways (TG) and AirAsia X (D7). Since passengers to and from Thailand are excluded from this thesis, TG was excluded as well.

Table 4.4 Airlines transporting the most Australia international passengers.

Year	Top 10 Airlines transporting the most Australia International Passengers									
	1	2	3	4	5	6	7	8	9	10
2012	QF	SQ	EK	VA	JQ	NZ	CX	MH	TG	D7
2011	QF	SQ	NZ	EK	JQ	VA	CX	MH	TG	D7
2010	QF	SQ	NZ	EK	JQ	VA	CX	MH	TG	D7
2009	QF	SQ	NZ	JQ	EK	VA	CX	TG	MH	D7
2008	QF	SQ	NZ	EK	JQ	CX	TG	MH	D7	GA

According to Alonso, Benito, Lonza, and Kousoulidou (2014) in a study of CO_2 emissions for flights within the EU, over 2/3 of the CO_2 emissions were on flights longer that 2500km. Australia has some of the longest and most emission intensive international routes in the world and even the shortest international flight are over 2000km. The 10 longest Australian international routes (Table 4.5) are to Dallas Fort Worth (DFW), Los Angeles (LAX), San Francisco (SFO), Dubai (DXB) and Abu Dhabi (AUH) from Melbourne (MEL), Sydney (SYD) and Brisbane (BNE).

Table 4.5 Longest Australia international routes.

	Top 10 Longest Australian International Routes									
	1	2	3	4	5	6	7	8	9	10
City Pairs	SYD-DFW	MEL-LAX	SYD-AUH	SYD-LAX	SYD-DXB	BNE-DXB	SYD-SFO	MEL-AUH	MEL-DXB	BNE-LAX
Distance (km)	13933	12883	12186	12186	12169	12104	12075	11777	11770	11658

This chapter focuses on airlines that transport the most passengers and flying on some of the longest and most emissions intensive routes. These airlines are Qantas, Jetstar, Virgin Australia, Emirates, Cathay Pacific, Air New Zealand, Malaysia Airlines, Singapore Airlines and their main competitors Delta Air Lines, United Airlines, Hawaiian Airlines, AirAsia X, Garuda, and Etihad. These airlines connect 30 airports/cities between Australia and the top seven countries (Supplementary data Table 4.9). The airline timetables for 2012 were purchased from Innovata (Innovata, 2014).

Narrow body aircraft in this thesis (i.e. A320, 737) are assumed to fly on short-haul international routes of less than 3000nm (5600km) with average passenger weight set at 85kg and checked baggage at 15kg giving an average passenger mass of 100kg; whereas wide body aircraft (i.e. A330, A340, A380, 747, 767, 777) are assumed to fly on medium and long haul international routes of greater than 3000nm (5600km) with the average passenger weight set at 85kg and checked baggage at 25kg giving an average passenger mass of 110kg.

The Australian Government's BITRE records the monthly passenger load factor (%) and amount of cargo (t) carried by each airline flying between Australia and each destination country (Bureau of Infrastructure Transport and Regional Economics (BITRE), 2014). Since the 2012 Airline Flight Schedules purchased from Innovata shows daily flights between cities, all flights for each airline between Australian cities and any city in the destination country are assumed to have the same passenger and cargo load factor for each month.

The monthly cargo load factor was determined by dividing the actual amount of cargo carried (and recorded by BITRE) by the maximum cargo load that can be carried. The aircraft's Operating Empty Weight (OEW) plus the weight of all passengers, checked baggage and maximum cargo must be below the aircraft's Maximum Zero Fuel Weight (MZFW). The volume of cargo and baggage must also fit in the volume of the aircraft's cargo hold. Different airlines may use different baggage and cargo density based on their own statistics but according to Reyd and Wouters (2005), the cargo on the lower deck of commercial flights have a density of 200-210kg/m^3. ICAO (2013b) recommended using 161kg/m^3 for freight and baggage density and jet fuel density of 0.8kg/L. In this thesis baggage density is set at 161kg/m^3 and freight density at 205kg/m^3. The combined weight of fuel, the aircraft's OEW, passengers, checked baggage and maximum cargo must not exceed the Maximum Take-Off Weight (MTOW) and fuel must not exceed the maximum fuel capacity.

The typical aircraft's cargo capacity, MTOW, MZFW and fuel capacity are published by the manufacturers and will be used in this thesis (Airbus, 2014a; Boeing, 2009, 2014a). The OEW is highly dependent on how each airline has fitted out their aircraft. Boeing publishes a typical OEW for all Boeing aircraft whereas Airbus does not. For all Airbus aircraft an approximate OEW that is published by the airlines will be used. Each airline's approximate OEW, MTOW, MZFW, cargo capacity and fuel capacity can be found in Supplementary data Table 4.14.

4.3.2 Validation

Since the CO_2 Profile Calculator (Figure 4.1) used in this thesis was based on the ICAO Carbon Calculator, the ICAO Carbon Calculator will be used to compare and validate the results (ICAO, 2014a, 2014b). The amount of CO_2 apportioned to a passenger on six Australian international routes determined by the ICAO Carbon Calculator and the CO_2 Profile Calculator use in this thesis is summarised in Table 4.6.

On average, the CO_2 Profile Calculator produced CO_2 estimates per passenger that were between 8.78% lower to 27.3% higher that ICAO Carbon Calculator for these six Australian international routes. These differences were mainly due to the updated CORINAIR fuel burn tables (Table 4.2) and actual numbers of seats and passengers per flight that was used in the CO_2 Profile Calculator. For example on the SYD-LAX route, the ICAO Carbon Calculator assumed the route was to be served by 777s and 747s. Qantas dominates this route and flies both 747s and A380s whereas Virgin, Delta and United flies the 777-300ER, 777-200LR and 747 respectively. In the updated fuel burn tables, the A380 burns 15.5% more fuel than the 747 and 777-300ER/200LR burns 12% more fuel than the original 777 fuel burn table used in the ICAO Carbon Calculator. On the BNE-LAX route, the ICAO Carbon Calculator assumed the route to be served by 747s and 777s with an average of 453 seats per flight. Virgin flies the 777-300ER with 361 seats and the Qantas 747 has 394 seats. The lower seat numbers equate to lower actual passenger numbers on each flight and higher CO_2 emissions per passenger on the route. The SYD-AUH route shows the biggest difference between the two calculators of 27.3%, Etihad dominates this route and flies A340-500/600 with updated fuel burn that is 36% higher than the original fuel burn for the A340.

On four of the six routes and selecting only the most efficient airline, the CO_2 Profile Calculator apportioned CO_2 to each passenger that closely matched the ICAO Carbon Calculator, the only exception being Sydney–Auckland (SYD-AKL) and Sydney-Abu Dhabi (SYD-AUH) routes. On the SYD-AKL route, the ICAO Carbon Calculator assumed each flight to consume 10,414kg of fuel and has on average 214 seats with a load factor of 75.6% (162 passengers) whereas the most efficient airline is Jetstar flying A320s, which has 180 seats with a load factor 78.5% (141 passengers) and used 30% less fuel (7,400kg). On SYD-AUH route ICAO Carbon Calculator has assumed each flight uses 98438kg of fuel and has 343 seats with a load factor of 79.2% (272 passengers) whereas the Virgin Australia’s 777-300ER has 361 seats with a load factor of 74.3% (268 passengers) but used more fuel (105,000kg).

These CO_2 Profile Calculator results correctly reflect the changes made to the CORINAIR fuel burn tables and the use of actual aircraft characteristics, passenger and cargo load on each route in 2012 when compared to the ICAO Carbon Calculator.

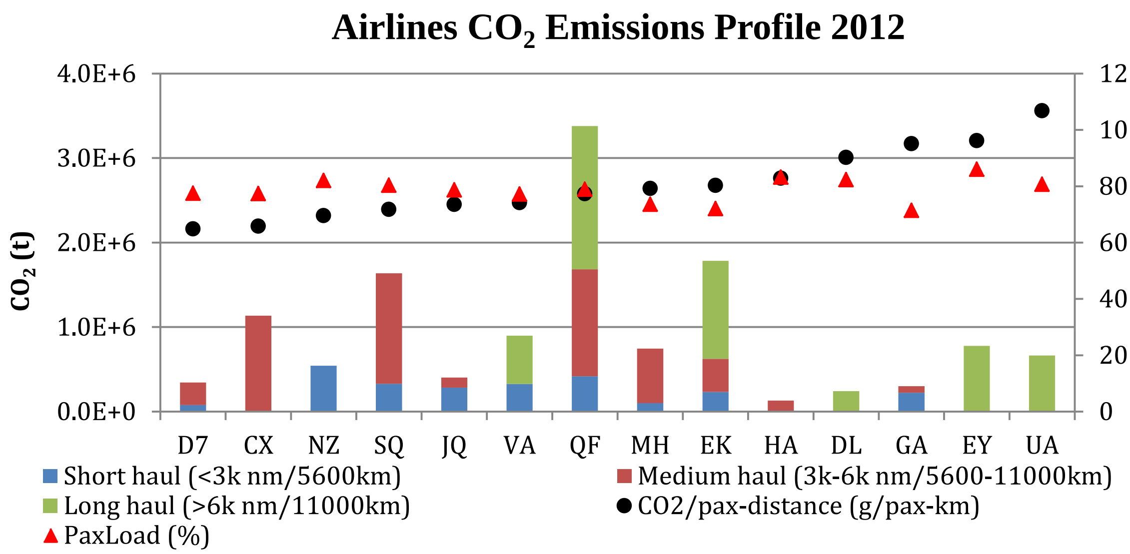
Table 4.6 CO_2 Profile Calculator Validation.

Route (one way)	ICAO Carbon Calculator[5]	CO_2 Profile Calculator (Figure 4.1)	
	Average amount of CO_2 (in kg) for an economy class passenger	Average amount of CO_2 (in kg) for a passenger in 2012	Average amount of CO_2 (in kg) for a passenger on the most efficient airline in 2012
SYD-LAX	932.66	1108.86 (+18.89%)	934.94 (+0.24%) Virgin Australia 777-300ER
BNE-LAX	876.2	976.21 (+11.41%)	919.76 (+4.97%) Virgin Australia 777-300ER
SYD-AUH	883.69	1124.95 (+27.3%)	1001.13 (+13.29%) Virgin Australia 777-300ER
SYD-AKL	190.52	173.82 (-8.78%)	163.97 (-13.94%) Jetstar A320
PER-KUL	285.19	301.26 (+5.64%)	275.82 (-3.29%) AirAsia X A330-300
SYD-HKG	489.67	527.17 (+7.66%)	489.48 (-0.04%) Cathay Pacific A330-300

4.4 Results & Discussions

The CO_2 emissions profiles of nine of the top 10 carriers by passenger numbers (i.e. Jetstar (JQ), Virgin Australia (VA), Qantas (QF), Emirates (EK), Cathay Pacific (CX), Malaysia Airlines (MH), AirAsia X (D7), Air New Zealand (NZ) and Singapore Airlines (SQ)) and their main competitors (i.e. Delta Air Lines (DL), United Airlines (UA), Etihad (EY), Hawaiian Airlines (HA) and Garuda GA)) flying between Australia and USA, New Zealand, Hong Kong, Malaysia, Singapore, UAE and Indonesia in 2012 are shown in Figure 4.2. These airlines are ranked from the most CO_2 efficient on the left to the least CO_2 efficient on the right in the Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5 (Supplementary data Table 4.15, Table 4.16, Table 4.17 and Table 4.18). AirAsia X is the most CO_2 efficient at 64.86g of CO_2 emitted for each passenger kilometre flown. This is due to the airline's modern efficient A330-300s and high-density seating. United Airlines is the least CO_2 efficient due to the use of older and less fuel efficient 747-400s on its flights to USA (mainland). In 2012, CO_2 efficiency of all three Australian based airlines was below the average of 80.6g of CO_2 per passenger-km. As expected Qantas (QF) is the largest emitter and Emirates, Singapore Airlines and Cathay Pacific are the largest foreign emitters.

[5] (ICAO, 2014a)

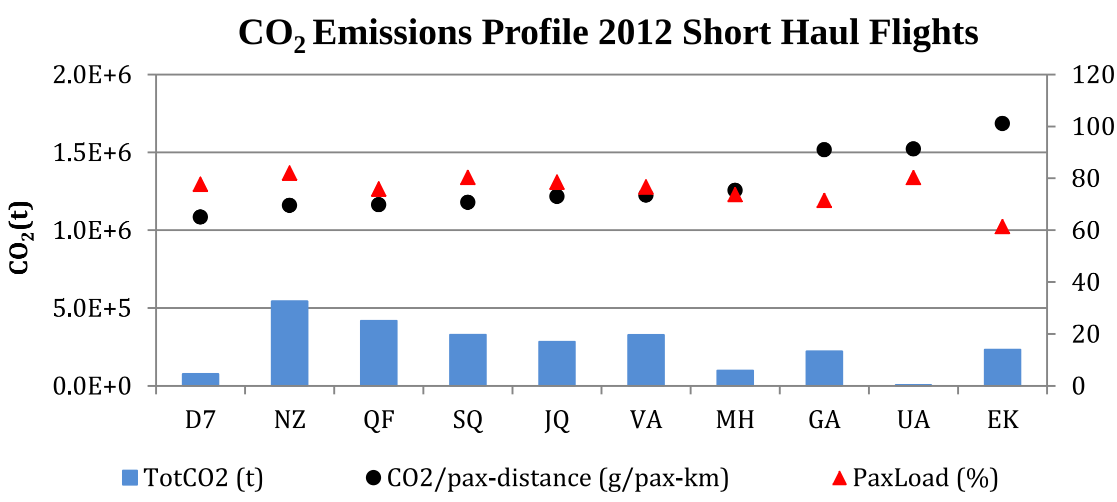


[6]

Figure 4.2 CO_2 Profile on Australian International Flights in 2012.

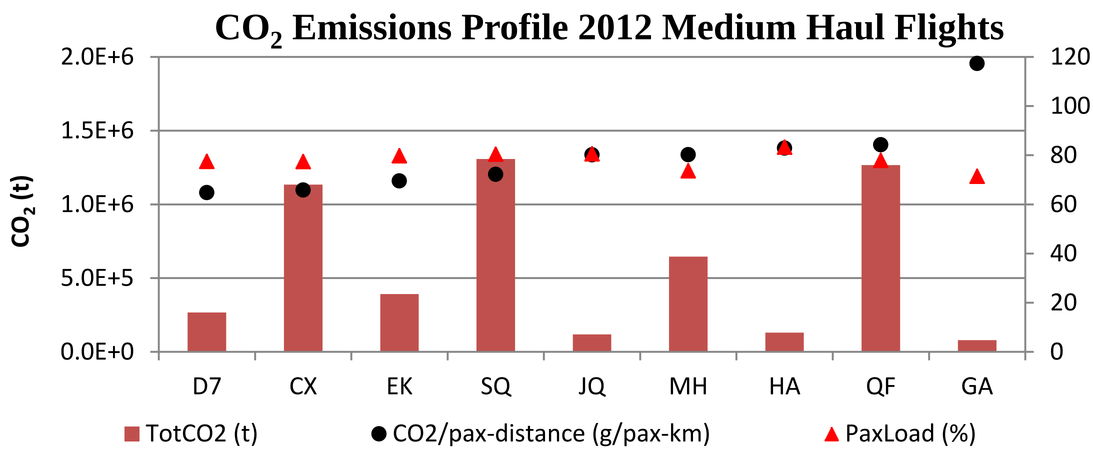
Short haul international flights account for 2.5Mt of emitted CO_2. Medium and long haul international flights both emitted over 5Mt of CO_2. In short, medium or long haul flights, the most CO_2 efficient airlines (AirAsia X, Emirates) emitted between 65g to 66g of CO_2 per passenger-km (Figure 4.3, Figure 4.4 and Figure 4.5 and Supplementary data Table 4.16, Table 4.17 and Table 4.18). Airlines can have large variations in CO_2 efficiencies depending on the distance flown, as demonstrated in Emirates estimates (101.09, 69.53, 65.5 g/passenger-km) and Qantas estimates (69.78, 84.23, 91.73 g/passenger-km) for short, medium and long haul flights respectively (Figure 4.3, Figure 4.4 and Figure 4.5). In 2012, all Australian based airlines are more CO_2 efficient than Emirates (80.32 g/passenger-km) but Emirates outperforms them all on medium and long haul flight (but not on short haul flights). The aircraft used on each flight will affect the total amount of CO_2 emitted and the payload (i.e. passengers and cargo) carried will determine the CO_2 efficiency of the flight.

[6] AirAsia X (D7), Cathay Pacific (CX), Air New Zealand (NZ), Singapore Airlines (SQ), Jetstar Airways (JQ), Virgin Australia (VA), Qantas (QF), Malaysia Airlines (MH), Emirates (EK), Hawaiian Airlines (HA), Delta Air Lines (DL), Garuda (GA), Etihad (EY), United Airlines (UA).



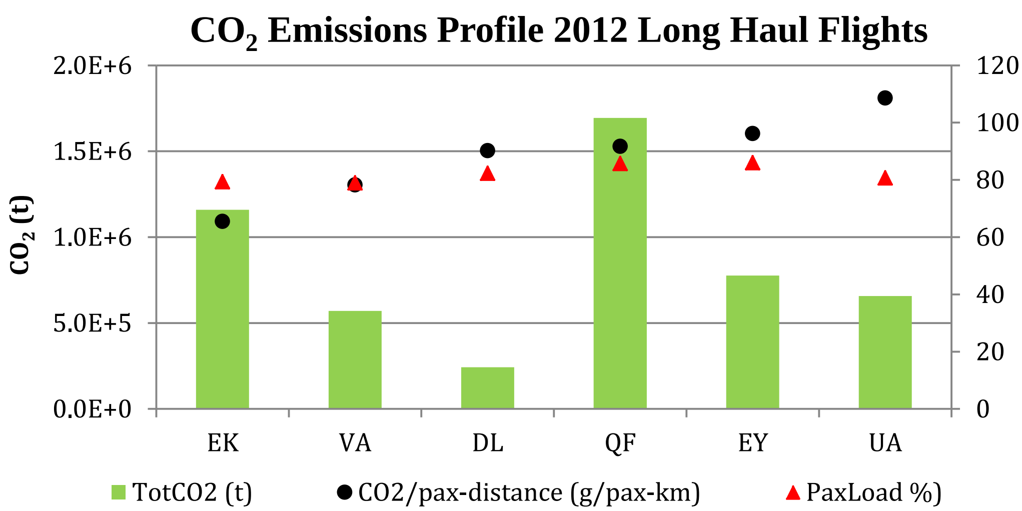
[7]

Figure 4.3 CO_2 Profile on Short Haul Australian International Flights in 2012.



[8]

Figure 4.4 CO_2 Profile on Medium Haul Australian International Flights in 2012.



[9]

Figure 4.5 CO_2 Profile on Long Haul Australian International Flights in 2012.

7AirAsia X (D7), Air New Zealand (NZ), Qantas (QF), Singapore Airlines (SQ), Jetstar Airways (JQ), Virgin Australia (VA), Malaysia Airlines (MH), Garuda (GA), United Airlines (UA), Emirates (EK).
8AirAsia X (D7), Cathay Pacific (CX), Emirates (EK), Singapore Airlines (SQ), Jetstar Airways (JQ), Malaysia Airlines (MH), Hawaiian Airlines (HA), Qantas (QF), Garuda (GA).
[9]Emirates (EK), Virgin Australia (VA), Delta Air Lines (DL), Qantas (QF), Etihad (EY), United Airlines (UA)

4.4.1 Aircraft used

On long haul international flights (Figure 4.5) the choice of aircraft can greatly affect the amount of CO_2 generated and CO_2 efficiency. On flights between Australia and USA (mainland), a variety of both old and new wide body aircraft are used. Qantas (QF) dominates these routes with over half of the seats and emissions generated. Qantas uses a mixed fleet of both older 747-400 and newer A380 aircraft whereas Virgin Australia (VA) uses the newer 777-300ER and United Airlines uses some of the oldest and least efficient 747-400 aircraft. Delta uses the 777-200LR which is a shortened 777-300ER that can fly up to a range of 17,000km but carrying a reduced payload (i.e. 269 versus 361 seats). The reduced payload makes the 777-200LR less CO_2 efficient than 777-300ER. For flights between Australia and UAE all the aircraft used are relatively new with Emirates having the best CO_2 efficiency by using a combination of A380 and 777-300ER whereas Etihad flies mainly the A340-500/600 and Virgin Australia flies the 777-300ER. Focusing on the Sydney-Los Angeles route (Figure 4.6), it can be seen very clearly that Virgin Australia's choice of 777-300ER has resulted in the lowest amount of CO_2 emitted per passenger-km flown of 76.72g even though it has the lowest passenger load factor of 79.9% on this route whereas United Airlines using older 747-400s is least efficient on this long haul international route.

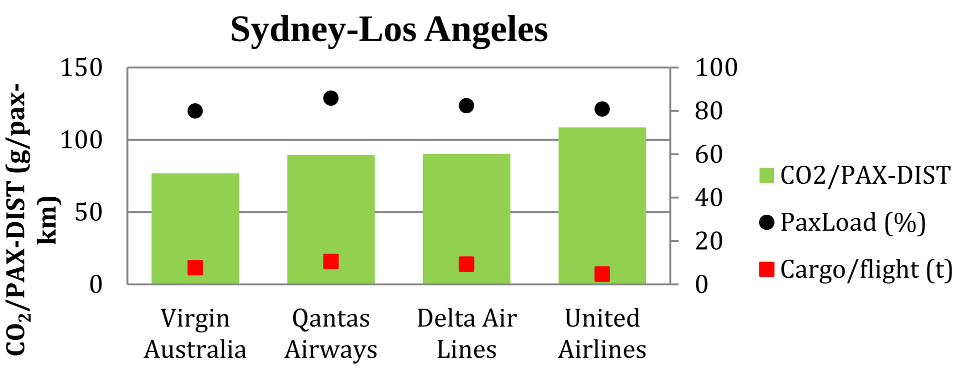
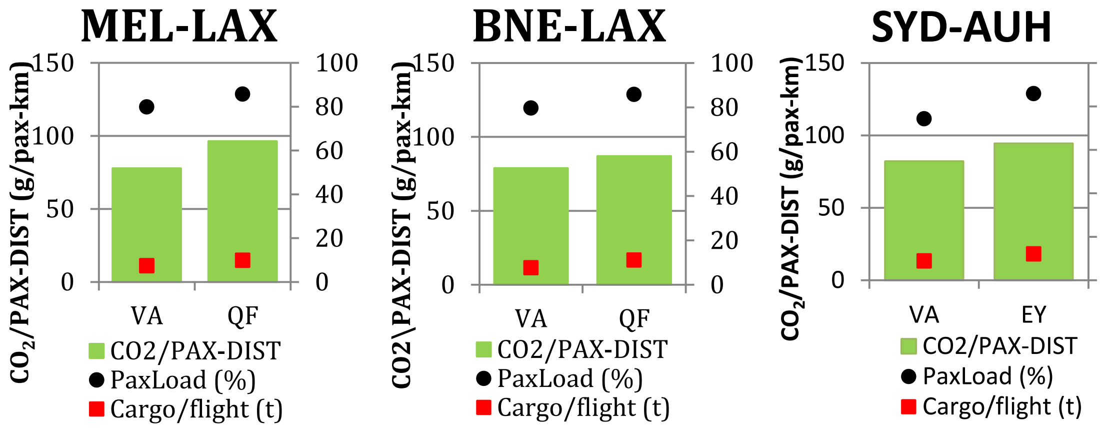


Figure 4.6 CO_2 Efficiency Virgin Australia v Qantas v Delta v United Airlines.

This is repeated on the Melbourne-Los Angeles (MEL-LAX), Brisbane-Los Angeles (BNE-LAX) and Sydney-Abu Dhabi (SYD-AUH) routes (Figure 4.7). Virgin Australia flies the two-engine 777-300ER aircraft on all three routes, Qantas flies four-engine A380 from Melbourne, 747-400 from Brisbane and Etihad (EY) flies four-engine A340 from Sydney. Virgin Australia's 777-300ER is again more CO_2 efficient even though it has lower passenger load factor and carrying less cargo per flight.



[10]

Figure 4.7 CO_2 Efficiency Virgin Australia v Qantas & Etihad.

On these long haul flights, selecting the "right" aircraft can greatly reduce the amount of CO_2 generated. Virgin Australia's 777-300ER emits less CO_2 and is the more CO_2 efficient aircraft when compared to its competitors on the same long haul city-pair routes (Figure 4.6 and Figure 4.7).

4.4.2 Number of Passengers carried

The number of passengers carried on each flight is dependent on the seat density and load factor. On the Australia-Malaysia routes, Malaysia Airlines carried more cargo per flight than AirAsia X (9.86t v 4.18t), this is equivalent to having extra 52 passengers but AirAsia X with a higher passengers load factor and utilizing denser seat configuration of 377-401 seats translates to an 18% better CO_2 efficiency (Figure 4.8).On the Melbourne to Kuala Lumpur and Brisbane/Gold Coast (OOL) to Kuala Lumpur routes both AirAsia X and Malaysia Airlines use A330-300s but Malaysia Airlines has 288-296 seats. The payload difference between these two airlines on these routes are summarised in Table 4.7. AirAsia X carries approximately 80 extra passengers on their flights and even though Malaysia Airlines carries 5t more cargo, it is no enough to make Malaysia Airline flights more CO_2 efficient.

[10] Virgin Australia (VA), Qantas (QF), Etihad (EY), Melbourne (MEL), Brisbane (BNE), Sydney (SYD), Los Angeles (LAX), Abu Dhabi (AUH)

Table 4.7 Payload comparison: AirAsia X versus Malaysia Airlines on MEL/BNE/OOL-KUL.

	AirAsia X	Malaysia Airlines
CO_2/pax-km (g/pax-km)	65	74
Number of Flights	1354	1988
Avg Distance/Flight (km)	6515.38	6472.48
Number of Seats/Flight	377-401	288-296
Paxload/Flight (%)	78	74
Num of Passengers/Flight	294-313	213-219
Cargo/Flight (t)	4.12	9.62
Payload/Flight (t)	36.46	33.71

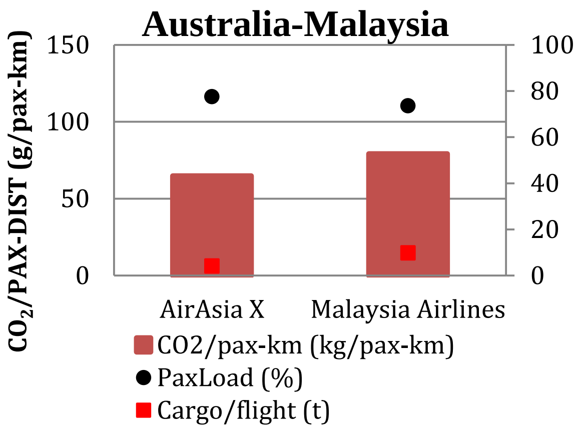


Figure 4.8 CO_2 Efficiency on Australia-Malaysia Flights.

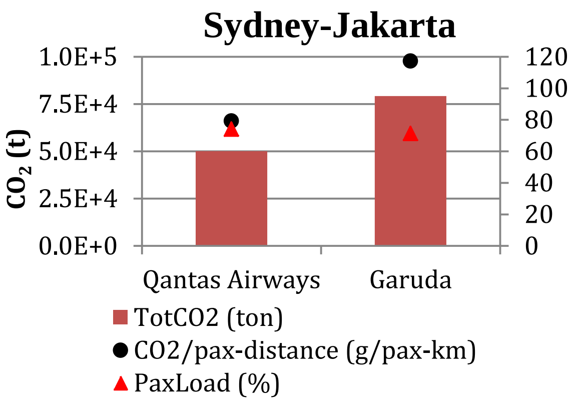


Figure 4.9 CO_2 Profile on Sydney-Jakarta Flights.

On the medium haul routes (Figure 4.4), Garuda flights are the least CO_2 efficient of those examined in this study. This is because of the low density seating on their A330-200 (222 seats), which is 40% lower than Qantas (303seats). On the Sydney-Jakarta route (Figure 4.9), Garuda's passenger load factor is above 70% but the low-density seating results in low passenger numbers and the worst CO_2 efficiency in this study.

On the long haul routes between Australia and UAE, Emirates, Etihad and Virgin Australia all use modern wide-bodied aircraft. Even though Emirates and Virgin Australia both use the 777-300ER, the former has higher density seating of 400 seats whereas the later has 361seats. The higher density seating in combination with the higher load factor on Emirates leads to higher passenger numbers and lower CO_2 emitted per passenger-km flown. Emirates fly a combination of higher seat density 777-300ER and A380 to produce the best CO_2 efficiency on long haul routes between Australia and UAE (Figure 4.10). Etihad has the worse CO_2 efficiency even though it has the highest load factor. This is because Etihad A340s are less fuel efficient than 777-300ER, has lower number of seats of between 240 and 286 and fewer passengers per flight (Figure 4.10 and Figure 4.11).

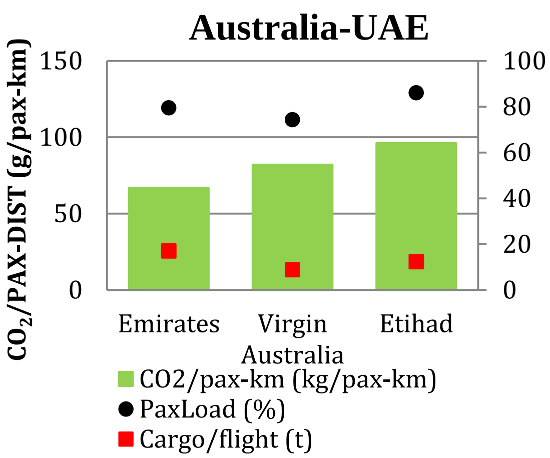


Figure 4.10 CO_2 Efficiency on Australia-UAE Flights.

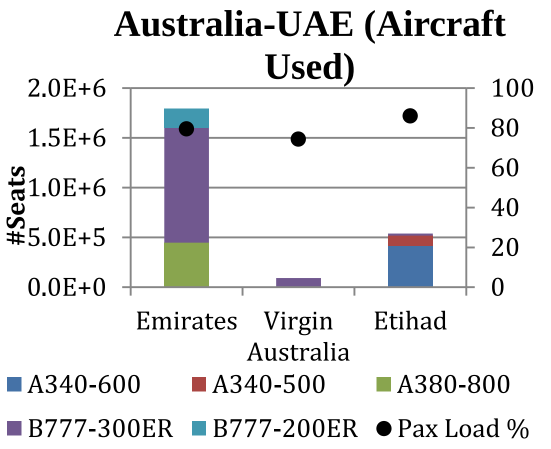


Figure 4.11 Aircraft used on Australia-UAE Flight

In 2012, passenger load factors on all international flight were on average above 70% but on short haul international flights the load factors on Emirates were the lowest of those estimated in this study (Figure 4.5). Flights between Australia and New Zealand are dominated by airlines based in both countries flying mainly narrow body A320s and 737s with load factors of 75% or more (Figure 4.12). Emirates and Taiwan based China Airlines exercise their 5^{th} freedom traffic rights and fly wide-bodied A380s, 777s and A330s between Australia and New Zealand (Figure 4.13). 5^{th} freedom traffic rights allow foreign airlines to transport passengers between Australia and another country that is not the airline's home country. These flights suffer from low passenger load factor of less than 62% and are CO_2 inefficient when compared to other airlines on this route. These low passenger loads were also observed on international 5^{th} freedom intra-EU flights serving UK (C. Miyoshi & Mason, 2009). Virgin Australia flying 737-800 and Emirates flying A380 and 777-300ER has roughly the same number of seats between Australia and New Zealand (Figure 4.13) but Virgin Australia has higher passenger load factor of 76.7% versus 61.4%, lower amount of CO_2 emitted of 1.8E5t versus 2.3E5t and more CO_2 efficient flights of 73.12g/passenger-km versus 101.09g/passenger-km (Figure 4.12).

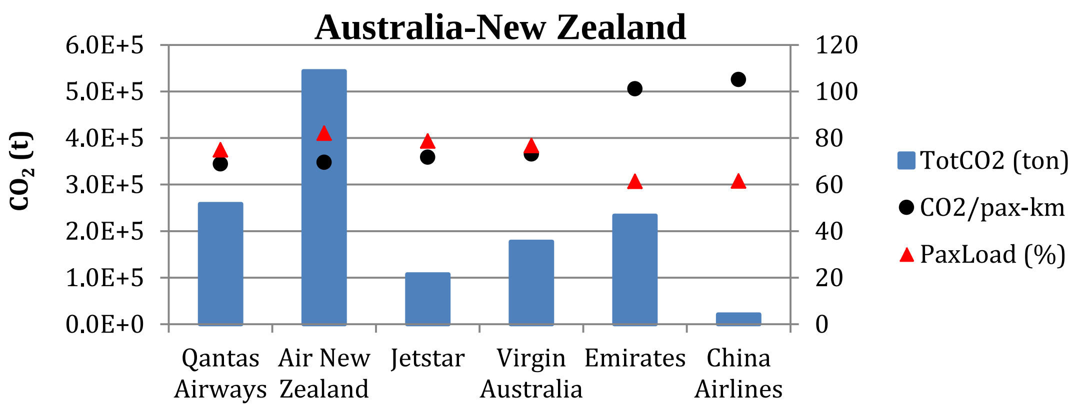


Figure 4.12 CO_2 Profile on Australia-New Zealand Flights.

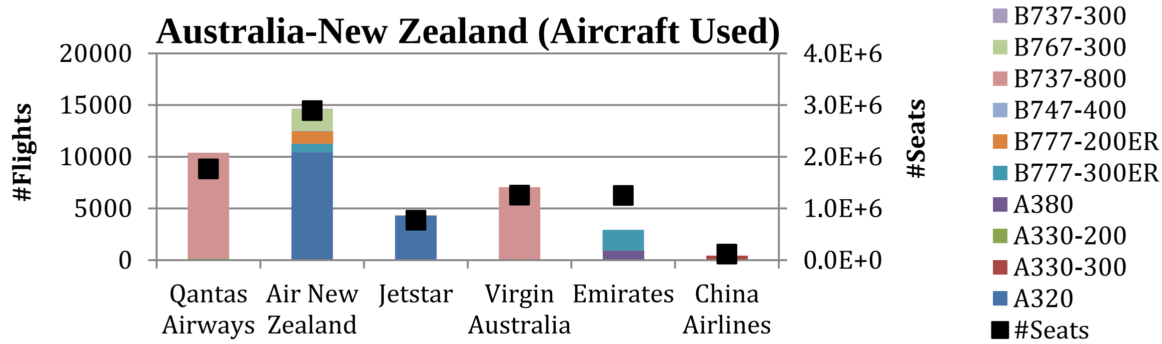


Figure 4.13 Aircraft Used on Australia-New Zealand Flights.

A more CO_2 efficient flight needs to have higher passenger payload. To achieve this, airlines must have both higher load factors and higher density seating. The 5^{th} freedom flights between Australia and New Zealand suffer from low passenger loads thus leading to some of the most CO_2 inefficient flights.

4.4.3 Amount of Cargo

The payload on each flight is made up of passengers, bags and freight. CO_2 efficiency is calculated by dividing the total amount of CO_2 emitted on each flight between each passenger plus bags and freight. On routes between Malaysia and Australia, Malaysia Airline was not as CO_2 efficient as AirAsia X even though it carried more cargo but fewer passengers. On medium haul flights (Figure 4.4), Cathay Pacific achieves similar CO_2 efficiency to AirAsia X and like AirAsia X; Cathay Pacific uses A330-300 on over 98% of its flights to Australia (Figure 4.14). Cathay Pacific has passenger load factor of 77.4% versus 77.53% on AirAsia X but uses lower density seating of 311-314 which is over 60 seats less than on AirAsia X (Table 4.8). Cathay Pacific achieved the second best CO_2 efficiency on medium haul routes by carrying more freight than AirAsia X on each flight (10.82t v 4.18t). The extra 6.64t of freight is equivalent to having an additional 60 passengers assuming each passenger and their checked bags weigh 110kg. The average payload on AirAsia X and Cathay Pacific flights is summarised in Table 4.8.

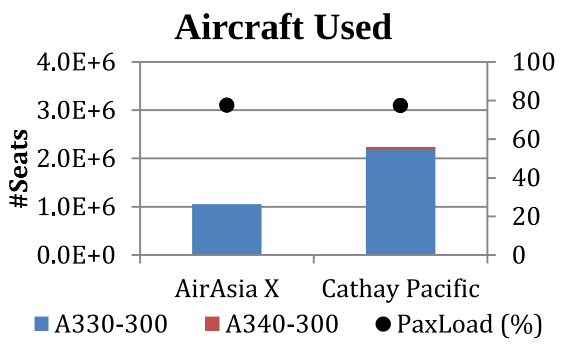


Figure 4.14 Aircraft used on AirAsia X v Cathay Pacific.

Table 4.8 Payload comparison: AirAsia X versus Cathay Pacific.

	AirAsia X	Cathay
CO_2/pax-km (g/pax-km)	64.86	65.79
CO_2/payload-km(g/kg-km)	0.59	0.60
Number of Flights	2719	7233
Avg Distance/Flight (km)	5855.35	7165.27
Number of Seats/flight	377-401	311-314
Pax load/Flight (%)	77.53	77.4
Num of Passengers/Flight	292-311	241-243
Avg Cargo/Flight (t)	4.18	10.82
Payload/Flight (t)	36.3-38.4	37.3-37.5

These results show that an airline can still achieve higher CO_2 efficiency by increasing it cargo payload to compensate for low passenger payload.

4.5 Conclusions

To determine the CO_2 profile of all airlines operating in the Australian international market in 2012, a CO_2 Profile Calculator was developed that uses airline's aircraft characteristics, passenger and cargo load on each international flight. The calculator did not take into consideration the airlines' business models but determines the airlines emissions efficiency relative to actual passengers and cargo carried. The methodology and results presented in this chapter can also be applied and extended to countries other than Australia that are also geographically isolated with relatively low and sparsely distributed populations (e.g. New Zealand, Island nations).

As expected, Qantas (the largest carrier in the Australia international aviation market) was the largest emitter in 2012. On Australian long haul routes, selecting the "right" aircraft can greatly reduce the total amount of emissions from a flight. The 777-300ER was more CO_2 efficient when compared to other aircraft used on the same long haul routes. AirAsia X configured their A330-300 with higher density seating, and when combined with high load factors, this approach achieved the best CO_2 efficiency on Australian flights. Cathay Pacific shows that increasing the amount of cargo carried on a flight improved their CO_2 efficiency to almost matching CO_2 efficiency of AirAsia X on medium haul international routes without the use of high-density seating. Emirates and China Airlines exercising their 5th freedom traffic right between Australia and New Zealand suffer from low load factor and low CO_2 efficiency.

Airlines can reduce CO_2 emissions and raise CO_2 efficiency by adopting new technology, optimising their flight operations and improving the management of their fleet. In this context, new technology can involve renewing their fleet with more fuel efficient aircraft or retrofitting their fleet with performance enhancing technology such as winglets, engines updates and using bio fuels. During each stage of the flight, airlines can reduce fuel burnt by optimising the speed, altitude, rate of climb and rate of decent, taxi-in and taxi-out of the flight. Airlines can optimise fleet operations by matching aircraft to payload, increasing payload, reducing turnaround/idle times and maintaining aircraft in the best operating conditions. The adoption of any of these emission mitigation measures is highly dependent on the price of fuel, economic growth and the costs and ease of implementation of these measures.

Additional research should be undertaken to determine the effects of pricing both CO_2 emissions and CO_2 efficiency on the cost of each emission mitigating measure for each airline. By knowing the CO_2 emissions profile, the relative cost of each emission mitigation measure and the expected emissions and efficiency improvements, policy makers can focus on researching and developing policies that can assist airlines in adopting the most effective emission mitigation measures that are also politically feasible.

Due to Australia's geographic isolation and low population, there are certain emission mitigation measures that are not viable. For example, in regions with large population centres, short haul international flights can be replaced by high-speed rail and hub and spoke networks can be replaced by smaller more efficient direct flights. Smaller direct long haul international flight will become more prevalent as airlines upgrade to new smaller efficient long haul aircraft. At present the quickest and most cost-effective way for Australia to transport both passengers and cargo internationally is by air.

4.6 Supplementary data

Table 4.9 Airport Locations.

Country	Country Code	City	Airport Code	Latitude	Longitude
Australia	AU	Sydney	SYD	-33.9329	151.1799
Australia	AU	Melbourne	MEL	-37.6696	144.8498
Australia	AU	Brisbane	BNE	-27.403	153.109
Australia	AU	Adelaide	ADL	-34.9382	138.5373
Australia	AU	Perth	PER	-31.9336	115.9602
Australia	AU	Gold Coast	OOL	-28.1661	153.5131
Australia	AU	Cairns	CNS	-16.8765	145.754
Australia	AU	Darwin	DRW	-12.4078	130.8775
Australia	AU	Sunshine Coast	MCY	-26.6054	153.0882
Australia	AU	Port Hedland	PHE	-20.3779	118.6316
USA	US	Guam	GUM	13.4928	144.8049
USA	US	Los Angeles	LAX	33.9434	-118.4083
USA	US	San Francisco	SFO	37.6152	-122.3899
USA	US	Dallas	DFW	32.8975	-97.0361
USA	US	Honolulu	HNL	21.3258	-157.9217
Singapore	SG	Singapore	SIN	1.3612	103.9902
United Arab Emirates	AE	Dubai	DXB	25.2487	55.3529
United Arab Emirates	AE	Abu Dhabi	AUH	24.4269	54.646
New Zealand	NZ	Auckland	AKL	-37.0048	174.7835
New Zealand	NZ	Christchurch	CHC	-43.4886	172.5389
New Zealand	NZ	Wellington	WLG	-41.329	174.8122
New Zealand	NZ	Queenstown	ZQN	-45.022	168.7391
New Zealand	NZ	Rotorua	ROT	-38.1098	176.3175
New Zealand	NZ	Dunedin	DUD	-45.9239	170.199
New Zealand	NZ	Hamilton	HLZ	-37.8662	175.336
Hong Kong (SAR)	HK	Hong Kong	HKG	22.3152	113.9365
Malaysia	MY	Kuala Lumpur	KUL	2.7443	101.7173
Malaysia	MY	Kota Kinabalu	BKI	5.924	116.0507
Indonesia	ID	Denpasar	DPS	-8.7481	115.1675
Indonesia	ID	Jakarta	CGK	-6.1306	106.6555

Table 4.10 Modified CORINAIR fuel burn table showing total fuel burn for flight distance of 125 to 1000nm.

	Distance (nm)				
Aircraft Fuel Burn (kg)	125.00	250.00	500.00	750.00	1000.00
A320/A319/737-800/900	1713.46	2602.18	3814.35	4902.62	6280.37
A321	1984.18	3013.32	4417.02	5677.23	7272.67
A330	4093.66	5862.43	8615.45	11359.97	14121.50
A340	5212.75	7709.96	11536.04	15382.76	19313.64
A380	7312.15	10462.29	15482.27	20502.24	25522.22
737-700	1522.97	2154.56	3432.19	4712.31	5987.43
747-100/200/300	6564.83	9419.78	14308.04	19196.29	24084.55
747-400/400ER	6330.86	9058.26	13404.56	17750.86	22097.16
767	3242.43	4606.58	6939.14	9271.69	11604.25
777-200/300/200ER	4819.58	7035.14	10130.36	13226.45	16363.80
777-300ER/200LR	5397.93	7879.36	11346.00	14813.62	18327.45

Table 4.11 Modified CORINAIR fuel burn table showing total fuel burn for flight distance of 1500 to 3500nm.

	Distance (nm)				
Aircraft Fuel Burn (kg)	1500.00	2000.00	2500.00	3000.00	3500.00
A320/A319/737-800/900	8681.96	11322.26	14005.80	16491.08	
A321	10053.71	13111.18	16218.71	19307.79	
A330	19790.45	25634.21	31714.79	38043.52	44311.94
A340	27381.12	35740.53	44465.93	53196.16	62388.44
A380	35714.41	46508.01	57149.66	68811.30	80720.97
737-700	8728.29	11559.25	14580.25	17671.63	20883.05
747-100/200/300	34170.53	44418.98	55255.17	66562.31	77909.24
747-400/400ER	30921.57	40266.67	49480.22	59576.88	69888.28
767	16487.19	21492.63	26540.70	32003.06	37705.80
777-200/300/200ER	22576.41	29225.68	36026.67	43143.25	50294.63
777-300ER/200LR	25285.58	32732.76	40349.88	48320.44	56329.98

Table 4.12 Modified CORINAIR fuel burn table showing total fuel burn for flight distance of 4000 to 6000nm.

	Distance (nm)				
Aircraft Fuel Burn (kg)	4000.00	4500.00	5000.00	5500.00	6000.00
A330	51005.69	57425.09	64238.47		
A340	71937.45	81707.93	92030.77	102772.88	113821.10
A380	93311.58	106244.41	119671.17	133463.74	148037.29
747-100/200/300	90362.10	103265.90	116703.31	130411.02	
747-400/400ER	80789.24	91986.50	103611.40	115553.02	128170.81
767	43475.10	49555.63	55862.56		
777-200/300/200ER	57904.29	65763.50	73655.15	82067.40	90693.23
777-300ER/200LR	64852.81	73655.12	82493.76	91915.49	101576.42

Table 4.13 Modified CORINAIR fuel burn table showing total fuel burn for flight distance of 6500 to 8000nm.

Aircraft Fuel Burn (kg)	Distance (nm) 6500.00	7000.00	7500.00	8000.00
A340	127793.38	139720.63	151990.87	
A380	163148.65	184392.90	200999.41	218120.41
747-400/400ER	141254.25	149606.45	162498.78	175734.10
777-200/300/200ER	517800.95	566755.42	515489.06	
777-300ER/200LR	103957.55	112811.41	121836.76	131033.61

Table 4.14 Aircraft Characteristics.

Airlines	**Aircraft**	**MTOW (kg)**	**OEW (kg)**	**MZFW (kg)**	**Fuel Cap (L)**	**Cargo Vol (m^3)**
Qantas	A330-200	233000	120559	170000	139090	132.4
Qantas	A330-300	212000	120311	164000	97530	158.4
Qantas	A380-800	560000	270015	361000	323546	175.2
Qantas	737-400	68039	33643	53070	23827	31.1
Qantas	737-800	79016	41413	62732	26022	44.1
Qantas	747-400	396894	179752	247208	216824	181
Qantas	747-400ER	412770	184567	251744	239363	151
Qantas	767-300	172365	87924	126099	91380	114.1
Virgin	737-700	69400	37648	54658	26022	27.4
Virgin	737-800	78245	41413	61689	26022	44.1
Virgin	777-300ER	351535	167829	237683	181283	213.8
Virgin	F-100	45810	24747	36740	13365	16.72
Jetstar	A320	77000	42000	60500	23859	37.42
Jetstar	A321	93000	49196	73800	26692	51.72
Jetstar	A330-200	233000	120559	170000	139090	132.4
Singapore	A330-300	230000	122200	173000	97530	158.4
Singapore	A380-800	560000	270015	361000	323546	175.2
Singapore	747-400	362874	179015	242672	204333	181
Singapore	777-200	263030	135600	195000	171170	160.3
Singapore	777-200ER	297550	141880	199580	171170	160.3
Singapore	777-300	299370	157800	224520	169210	213.9
Singapore	777-300ER	351535	167829	237683	181283	213.8
Emirates	A380-800	560000	270281	361000	323546	175.2
Emirates	777-200LR	347452	146690	209106	202570	160.2
Emirates	777-300ER	351535	167829	237683	181283	213.8
Delta	777-200LR	347452	145150	209106	181283	160.2
United	737-700	69400	37648	54658	26022	27.4
United	737-800	78245	41413	61689	26022	44.1
United	747-400	396890	183520	251740	216840	181
United	777-200ER	297550	144330	199580	171170	160.3
AirAsia X	A330-300	233000	130000	175000	97530	158.4
Air NZ	A320	73500	42100	61000	23859	37.42
Air NZ	737-300	63276	32904	49714	23827	22.4

Airlines	**Aircraft**	**MTOW (kg)**	**OEW (kg)**	**MZFW (kg)**	**Fuel Cap (L)**	**Cargo Vol (m^3)**
Air NZ	747-400	362874	178756	242672	203521	181
Air NZ	767-300	186880	90011	133810	91380	114.1
Air NZ	777-200ER	297550	141880	199580	171170	160.3
Air NZ	777-300ER	351535	167829	237683	181283	213.8
Garuda	A330-200	230000	119600	168000	139090	132.4
Garuda	A330-300	235000	126800	173000	97530	158.4
Garuda	737-800	79016	41413	62732	26022	44.1
Cathay	A330-300	233000	130000	175000	97530	158.4
Cathay	A340-300	275000	136929	180000	140640	158.4
Cathay	747-400	396894	179752	247208	216824	181
Cathay	777-200	247200	137160	190500	117340	160.3
Cathay	777-300	299370	157800	224530	169210	213.9
Cathay	777-300ER	351535	167829	237683	181283	213.8
Malaysia	A330-200	230000	119600	168000	139090	132.4
Malaysia	A330-300	230000	122200	173000	97530	158.4
Malaysia	A380-800	560000	270015	361000	323546	175.2
Malaysia	737-800	79016	41413	62732	26022	44.1
Malaysia	747-400	396894	179015	246074	216824	181
Malaysia	777-200ER	297550	141880	199580	171170	160.3
Etihad	A330-200	230000	119600	168000	139090	132.4
Etihad	A340-500	368000	170900	225000	214808	149.7
Etihad	A340-600	368000	177800	245000	195010	201.7
Etihad	777-300ER	351535	167829	237683	181283	213.8
Hawaiian	A330-200	238000	119600	170000	139090	132.4
Hawaiian	767-300	186880	90011	133810	91380	114.1
China	A330-300	230000	122200	173000	97530	158.4

Table 4.15 2012 Emissions Profile

Airlines	Tot CO_2 (t)	CO_2/pax-distance (g/pax-km)	CO_2/payload-distance (g/kg-km)
AirAsia X	344,078.45	64.86	0.59
Cathay Pacific	1,134,113.79	65.79	0.60
Air New Zealand	543,549.59	69.56	0.67
Singapore Airlines	1,636,828.03	71.75	0.65
Jetstar	530,579.78	73.18	0.71
Virgin Australia	898,027.53	74.15	0.73
Qantas Airways	3,378,303.70	77.35	0.73
Malaysian Airlines	744,833.13	79.19	0.72
Emirates	1,784,305.20	80.32	0.73
Hawaiian Airlines	130,663.72	82.85	0.75
Delta Air Lines	242,331.69	90.24	0.82
Garuda	301,477.65	95.08	0.90
Etihad	776,724.89	96.19	0.87
United Airlines	663,079.30	106.62	0.98
Total	13,108,896.43	75.68	0.71

Table 4.16 2012 Emissions Profile on Short Haul Routes

Airlines	Tot CO_2 (t)	CO_2/pax-distance (g/pax-km)	CO_2/payload-distance (g/kg-km)
AirAsia X	76,634.43	65.05	0.59
Air New Zealand	543,549.59	69.56	0.67
Qantas Airways	418,014.56	69.78	0.69
Singapore Airlines	329,298.35	70.77	0.64
Jetstar	314,791.44	72.23	0.71
Virgin Australia	327,498.07	73.51	0.73
Malaysia Airlines	99,248.83	75.33	0.69
Garuda	222,204.72	91.03	0.87
United Airlines	5,905.91	89.14	0.89
Emirates	233,250.85	101.09	0.92
Total	2,570,396.74	73.81	0.72

Table 4.17 2012 Emissions Profile on Medium Haul Routes

Airlines	Tot CO_2 (t)	CO_2/pax-distance (g/pax-km)	CO_2/payload-distance (g/kg-km)
AirAsia X	267,444.03	64.78	0.59
Cathay Pacific	1,134,113.79	65.79	0.60
Emirates	391,841.87	69.53	0.63
Singapore Airlines	1,307,529.68	72.19	0.66
Jetstar	215,788.33	79.30	0.72
Malaysia Airlines	645,584.29	80.20	0.73
Hawaiian Airlines	130,663.72	82.85	0.75
Qantas Airways	1,266,379.93	84.23	0.77
Garuda	79,272.93	117.28	1.07
Total	5,438,618.57	75.10	0.68

Table 4.18 2012 Emissions Profile on Long Haul Routes

Airlines	Tot CO_2 (t)	CO_2/pax-distance (g/pax-km)	CO_2/payload-distance (g/kg-km)
Emirates	1,159,212.48	65.50	0.59
Virgin Australia	570,529.46	78.26	0.71
Delta Air Lines	242,331.69	90.24	0.82
Qantas Airways	1,693,909.20	91.73	0.83
Etihad	776,724.89	96.19	0.87
United Airlines	657,173.39	108.69	0.99
Total	5,099,881.11	86.07	0.78

Chapter 5. A study of the abatement options available to reduce carbon emissions from Australian international flights

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Chapter Summary

In this chapter, five scenarios were developed to evaluate abatement options that have been or will be implemented by airlines flying on Australian international routes. Analysis reveals that by acquiring more efficient aircraft and increasing the average number of passengers per flight by 10%, 15.6Mt and 29.2Mt of CO_2 would likely be emitted in 2020 and 2033 respectively, with CO_2 emissions increasing at 6.1% per annum and CO_2 efficiency dropping from 59.38g/pax-km in 2020 to 51.02g/pax-km in 2033. To achieve carbon neutral growth after 2020, additional abatement options will be required to reduce CO_2 emissions by a further 13.6Mt (i.e. 46.6%) in 2033.

5.1 Introduction

In 2012, 14 airlines transported 72% of international passengers into and out of Australia and generated a combined total of 13.1Mt of CO_2 emissions. Even though almost 60% of Australian international flights are short haul (i.e. under 5600km), they account for around 20% of the emissions with long and medium haul flights i.e. flight over 5600km accounting for 10.5Mt. Australian carriers account for just over a third of the total emissions with Qantas producing the lion's share at 3.4Mt (25.8%) of CO_2 and Virgin Australia and Jetstar producing 898kt and 530kt respectively (Chapter 4 and Yin et al. (2015)). Between 2013 and 2033, passengers and freight in the Asia-Pacific region will increase by 6% and 5% per annum respectively (Airbus, 2014b; Boeing, 2014b). At this rate, passenger numbers and cargo will double by 2024 and 2026, and triple by 2031 and 2034 respectively. In this chapter the amount of CO_2 emitted and CO_2 efficiency from a business-as-usual (BAU) scenario and four other scenarios are presented. In each of these four scenarios, a number of abatement options were combined together to determine their effectiveness at reducing emissions. These abatement options are assumed to be independent and have no flow on effects on passenger and freight growth.

International Air Transport Association (IATA) (2009) has committed to 1.5% fuel efficiency improvement from 2009 to 2020, carbon neutral growth from 2020, and 50% reduction in CO_2

emissions by 2050 when compared to 2005 levels . In the airline-aviation industry, abatement options that are available for reducing CO_2 emissions fall under the following categories: aircraft operations; infrastructure; aviation technologies; alternative fuels and behavioural change (Banbury, Behrens, Bowell, et al., 2009; Banbury, Behrens, Browell, et al., 2009; Braathen et al., 2012; Commonwealth of Australia, 2012; L. M. Dray et al., 2009; Farries & Eyers, 2008; Green et al., 2005; Holland et al., 2011; Kar et al., 2010; Morris, Rowbotham, Morrell, et al., 2009; Sustainable Aviation, 2012). According to IATA, aviation technologies can reduce CO_2 emissions by up to 40%, infrastructure improvements could save up to 12%, efficient aircraft operations will add up to 3% and radical technologies, biofuels and market based measures will be required to achieve carbon neutral growth after 2020 (Banbury, Behrens, Bowell, et al., 2009; International Air Transport Association (IATA), 2009; International Air Transport Association (IATA), Georgia Tech, & German Aerospace Center (DLR), 2013). Biofuels can reduce lifecycle emissions from between 10% to 100% when compared to traditional aviation fuel but there are many challenges such as sufficient sustainably grown biomass, high refining costs, demand from other industries, lack of policy incentives and low cost of traditional aviation fuel, to name but a few (Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2011; Gegg, Budd, & Ison, 2014; Gegg et al., 2015; Stratton et al., 2010). First generation biofuels are not suitable for aviation but 2nd and 3rd generation 30-50% biofuels mix with a lifecycle emissions reduction of at least 50% has the potential to achieve up to 25% fleet wide CO_2 reduction by 2050 (Farries & Eyers, 2008). According to Commonwealth Scientific and Industrial Research Organisation (CSIRO) (2011) if 5% of all aviation fuel used in Australia and New Zealand were replaced with biofuel in 2020 and 40% by 2050, their models showed that by 2030 there would be a 17% reduction in aviation greenhouse gas emissions. Australia's Air Traffic Management (ATM) is at 98%-99% efficiency and further improvements to ATM will reduce extra fuel burned from flying on non-optimal routes, queuing or holding (Commonwealth of Australia, 2012). The rise in passenger and cargo traffic from 2013 to 2033 will lead to additional flights which in turn may increase queuing, holding and emissions. ATM improvements may require new equipment installed at airports and on aircraft and additional training for both airline's crew and air traffic management's staff.

This chapter focuses on abatement options that airlines have recently implemented or will soon be implementing, like changing their operations, retrofitting their existing fleet or purchasing new aircraft. These abatement options will have minimal dependence on other stakeholders such as ATM and airport operators. Biofuels were excluded from this thesis since it is unclear what the lifecycle reduction for Australian aviation biofuel will be when they are introduced. The results in this chapter can easily be updated by reducing the CO_2 generated according to the biofuels lifecycle emissions savings. This chapter also assumes that the abatement options do not interact with each other in any way and that the adoption of one abatement option does not affect the effectiveness of any later adoption of other options. This of course might not be the case. For example some lightweight seats are integrated with lightweight inflight entertainment (IFE) systems and are narrower and thinner which could lead to an increase in the number of seats on each flight. Increasing seat count can lead to more passengers carried on each flight thereby reducing the need to purchase new aircraft. The objective of this chapter is to determine the maximum amount of emissions reduction for each of these abatement options and whether carbon neutral growth is achievable using only these abatement options after 2020.

This chapter is organised as follows. The abatement options with their associated fuel and weight savings are presented in section 5.2. The amount of fuel saved as a function of weight saved for each aircraft type can be found in the section 5.6. The business-as-usual (BAU) and four alternative scenarios are introduced in section 5.3. Each scenario defines the timeline that a subset of abatement options will be implemented. This section also describes the updates made to the original model presented in Chapter 4 (and Yin et al. (2015)). In section 5.4, CO_2 emissions profiles for five scenarios are presented. Finally conclusions are presented in section 5.5.

5.2 Theory/Calculation

5.2.1 Abatement Options

To decrease the amount of fuel used for each passenger or each kg of payload, an airline can increase the payload (passengers and cargo) or decrease fuel used on each flight. Payload on each flight is dependent on many factors including but not limited to flight schedule, code-sharing agreements with other airlines, type of aircraft, business model, ticket prices, and general state of the economy. The amount of fuel an aircraft uses is also dependent on many factors including but not limited to the aircraft’s maintenance interval, weight, age and aerodynamic efficiency. Technologies can be retrofitted to an existing aircraft to reduce drag and improve fuel efficiency but these are limited to small changes such as adding winglets or riblets. Retrofitting with lightweight equipment such as seats, trolleys, galleys, carpets, IFE systems or removing non-essential equipment or more cleaning can reduce aircraft’s weight. Each kg of weight saved equates to $183.60 of fuel savings per year assuming a fuel cost of $1025/tonne and 4500 flying hours per year (Wren, 2011). New lightweight seats are slimmer or narrower and new lightweight cabin infrastructure such as smaller toilets and galleys will reduce space occupied thus allowing airlines to increase the number of seats on their aircraft. According to Farries and Eyers (2008) retrofitting an existing fleet of aircraft usually result in less than 5% savings. Other technological improvements such as new engines and wings can result in larger efficiency improvements but can only be applied to newer versions of the same aircraft type and cannot be retrofitted onto existing aircraft. Retiring less efficient aircraft and introducing new or revolutionary equipment may achieve the largest fuel efficiency improvements.

5.2.1.1 Modifying airline operations

The range of airlines operations that can be modified and improved so as to reduce CO_2 emissions may include using airport power instead of the aircraft's Auxiliary Power Unit (APU), washing the engines more often, reducing the number engines used during taxi and towing aircraft between the gates and runways. The amount of CO_2 emissions saved when airlines reduce the number of engines used during taxiing and washing their aircraft's engines are included in this chapter because these options do not depend on new infrastructure or services provided by other stakeholders like airports or agreements with other airlines. Lufthansa claims that their Technik Cyclean Engine Wash process for cleaning aircraft engines reduces fuel burn by up to 1% whereas Jetstar and Virgin Australia both use Pratt & Whitney's EcoPower Engine Wash process which reduces fuel burn by up to 1.2% (Lufthansa Technik, 2015; Pratt & Whitney, 2010). Reducing the number of engines used during the taxiing phase of the flight has shown to reduce fuel burn by 20 to 45% during that phase (Deonandan & Balakrishnan, 2010; Sustainable Aviation, 2010).

Altering the flight schedule, joint ventures with other airlines, code sharing, choosing the correct sized aircraft for the route, adjusting ticket prices and modifying the airline's business model can all have an effect on the payload on each flight. By increasing the payload on each flight, an airline can reduce the number of flights required. Payload increase is not tied to any specific abatement option and in this chapter passenger numbers on each flight were increased by 5% and 10% to determine the amount of CO_2 saved.

Table 5.1. Fuel saved by updating airline operations

Abatement Options	Fuel Saved
Engine Wash (2-3 washes per year)	Up to 1.2%
Reduce Engine Taxi	20% during taxi phase

5.2.1.2 Retrofitting fleet

To improve the airline's CO_2 emissions profile on Australia international routes, airlines can reduce the fuel burned on each flight by reducing the aircraft's weight. This can range from fitting lightweight seats, interior, IFE systems, electronic flight bags (EFBs) and carpets to removing unnecessary weight like magazines, drinking water and equipment. In this thesis three light weighting options were considered namely replacing the paper-based flight bags with iPad based EFBs, installing lightweight seats and IFE systems. The amount of weight saved by selecting lighter equipment is highly dependent on equipment manufacturer, equipment selected and configuration that airlines have selected for their aircraft. For example the Recaro BL3520 seat saves 4.3kg per seat, Expliseat seat saves about 4kg per seat and Austrian Airlines saved at least 3kg per seat with their new Recaro seat (Eden, 2013; Gubisch, 2010; Kaminski-morrow, 2010). By using lightweight seats, airlines can increase seat count but in this thesis seat count is unchanged and each lightweight seat saves 4kg/seat. There are many manufacturers and types of IFE systems, this can range from wireless tablets based systems to large screen seat back system. Seat back IFE systems can be connected by hardwired cables with some of the hardware placed under the seats. New seat back systems are replacing these cable based systems with fibre or wireless based systems to improve not only the amount of entertainment programs but also to reduce weight. Lufthansa's BoardConnect wireless IFE systems save 360kg on a 737, 500kg on a 767, 390kg on a A321 and 780kg on a A340-600 (Lufthansa Systems, 2012). Whereas Lumexis Fibre to the seat (FTTS) IFE systems weight 5.6lb instead of 14lbs/seat (Ramsey, 2011). Finally American Airlines replaced a 35lb traditional paper based flight bag with two iPads EFB on their planes (Hughes, 2013). Table 5.11 and Table 5.12 summarise the fuel saved for the amount of weight reduced on each Boeing and Airbus aircraft respectively.

The other abatement options involve retrofitting current fleet with drag reducing winglets. Fuel saving 767 winglets, 737 scimitar winglets and A320 Sharklets are the only aerodynamic "aids" that are included in this thesis (Airbus, 2012a; Aviation Partners Boeing, 2015). The amount of fuel saved is dependent on the aircraft and distance flown and can be up to 5.7% over the standard version of the aircraft. Table 5.2 summarises the weight and fuel saved by each abatement option used in the model.

Table 5.2. Fuel saved by modifying aircraft

Abatement Options	Weight Saved (kg)
Lightweight Seats	4kg/seat
iPad Electronic Flight Bag	14.65kg/iPad
Lightweight IFE	Lumexis FTTS saves 3.8kg/seat
Abatement Options	**Fuel Saved (%)**
737NG scimitar winglets	1.0% @ 500nm 1.6% @ 1000nm 2.0% @ 2000nm 2.2% @ 3000nm
767-300 winglets	3.0% @ 1000nm 4.0% @ 2000nm 5.0% @ 4000nm 5.7% @ 6000nm
A320 Sharklets	2.5% @ 1000nm 3.5% @ 2500nm

5.2.1.3 Acquiring new aircraft

Airliners can reduce CO_2 emitted for each international passenger or kg of payload by acquiring more efficient aircraft to service the growth in passengers and cargo and also to replace less efficient aircraft in their fleet. Aircraft manufacturers tend to introduce new more efficient aircraft to supersede a similar sized less efficient aircraft. For example 787 supersedes the 767, 777-300ER/747-8 supersedes 747-400, and A320NEO supersedes A320. Airlines can sometimes downsize to a smaller aircraft with similar range as their superseded aircraft but can maintain the same number of seats on the route by increasing the flight frequency. A newly designed aircraft that supersedes an older model will produce at least 20% fuel savings whereas adding new engines or wings to an older model will generate less than 20% fuel savings (Banbury, Behrens, Bowell, et al., 2009; International Air Transport Association (IATA) et al., 2013). Abatement options in Table 5.3 identify the more efficient aircraft acquired to renew the 2012 fleet and also to fly the growth in passengers and cargo from 2013 to 2033.

Table 5.3. Fuel saved by renewing fleet

Abatement Options	Fuel Saved	Reference
777-300ER (replace 747-400)	17% on short haul 20% on medium haul 25% on long haul compared to 777-300ER	(European Environment Agency, 2006; Horton, 2010)
787-8 (replace 767 and A330-200/300)	20% of 767	(CAPA - Centre for Aviation, 2013; Trimble, 2014)
787-9 (replaces Qantas 747-400)	30% on long haul (30% of 747-400)	(European Environment Agency, 2006; Qantas, 2015)
A320NEO (replace A320/A321)	15% of A320	(Roewe, 2014; Rothman, 2014)
737MAX (replace 737-800)	14% of 737NG	(Teal, 2014)
777-8X/9X (replace 777-200LR/300ER)	16% of 777-300ER	(Norris, 2013)

5.3 Method

To transport the additional 6% increase in passenger and 5% increase in cargo traffic per annum in the Asia-Pacific region, airlines flying into and out of Australia will need to add extra flights, add extra seats on existing aircraft and/or increase payload on each flight. In this thesis, the number of seats on each flight will remain unchanged on the same or equivalent aircraft used for each short, medium or long haul flight but the number of flights and passenger numbers on each flight will increase to service this growth. The model used in (Chapter 4 and Yin et al. (2015)) in determining the 2012 carbon profile of Australian international flight was modified with the amount of fuel used by each aircraft type adjusted to reflect the fuel savings from each abatement option in Table 5.1 and Table 5.2. Abatement options in Table 5.3 summarised the amount of fuel saved by these new aircraft over the superseded aircraft. To keep the model simple, the fuel used (CO_2 emitted) on the routes flown by all superseded aircraft were reduced by the predicted % of fuel (CO_2) savings. For example, Boeing claims 787 is approximately 20% more fuel efficient than the 767/A330, CO_2 emitted on routes flown by these two aircraft types were reduced by 20% when they were replaced by 787 in the model. The updated model shows the maximum % of emissions reduction if airlines implement these abatement options on all applicable aircraft at once even though it may take many years to install or renew their entire fleet in normal practice. In the USA, it can take between 10 to15 years from when a new aircraft is introduced to when the entire US fleet is replaced (J. Lee & Mo, 2011). Finally the amount of fuel used on each flight was not adjusted to compensate for the age of the aircraft.

A business-as-usual (BAU) scenario and four alternative scenarios were studied (Table 5.4). These four alternative scenarios represent running the model with a subset of abatement options to determine their effectiveness at reducing the growth in CO_2 and improving CO_2 efficiency in the Australian international aviation market annually from 2013 to 2033.

Table 5.4. Scenario overview

Scenario	Overview
1	This is the BAU scenario, which assumes that all airlines flying Australian international routes will emit CO_2 at the same rate as in 2012.
2	In this scenario, current airlines' fleet are retrofitted with emissions reducing technologies and airline operations are updated (Table 5.1, Table 5.2). Passenger and cargo growth will be serviced by acquiring and flying the most utilised aircraft in short, medium and long haul routes i.e. the 737NGs/A320s, A330s and 777-300ERs from 2013 to 2033. These new aircraft will also have emissions reducing technologies installed and airline operations updated to reduce even more CO_2 emissions.
3	Scenario 3 is similar to Scenario 2 except that all non-Australian airlines' 747 flights are replaced by 777-300ER flights and all Qantas 747 flights are replaced by 787-9 flights.
4	This scenario determines the effectiveness of renewing and flying the most efficient fleet at reducing CO_2 emissions. In the current fleet, non-Australian airlines' 747s are replaced by 777-300ERs, Qantas 747s are replaced by 787-9s, 777-300ERs are replaced by 777Xs on long haul flights, 787s replaced both A330s and 767s on medium haul flights and in short haul flights, 737NGs/A320s are replaced by 737MAXs/A320NEOs. Passenger and cargo growth will be serviced by acquiring and flying the most utilised aircraft such as 737s/A320s, A330s and 777s before upgrading to even more efficient aircraft such as 777Xs, 737MAXs, A320NEOs and 787s when they become available . These aircraft are introduced under the same timeline used to renew the 2012 fleet. No aircraft are retrofitted with additional emissions reducing technologies and airline operations are not updated.
5	In this scenario the payload per flight in Scenario 2 to 4 are increased to determine the additional emissions saved in these 3 scenarios. The numbers of passengers per short, medium and long haul flight are increased by 5% and 10% thereby reducing the number of flights required to transport the same number of passengers.

Scenarios 2 to 4 are simulated as a combination of modifications and improvements made to current fleet and the acquisition of a fleet of new aircraft to service passenger and cargo growth (Figure 5.1). Since airlines will introduce improvements or acquire new aircraft at different times over the next 20 years, strategies in these two steps will indicate a timeline when these modifications or aircraft acquisitions will take place in 2013 to 2033.

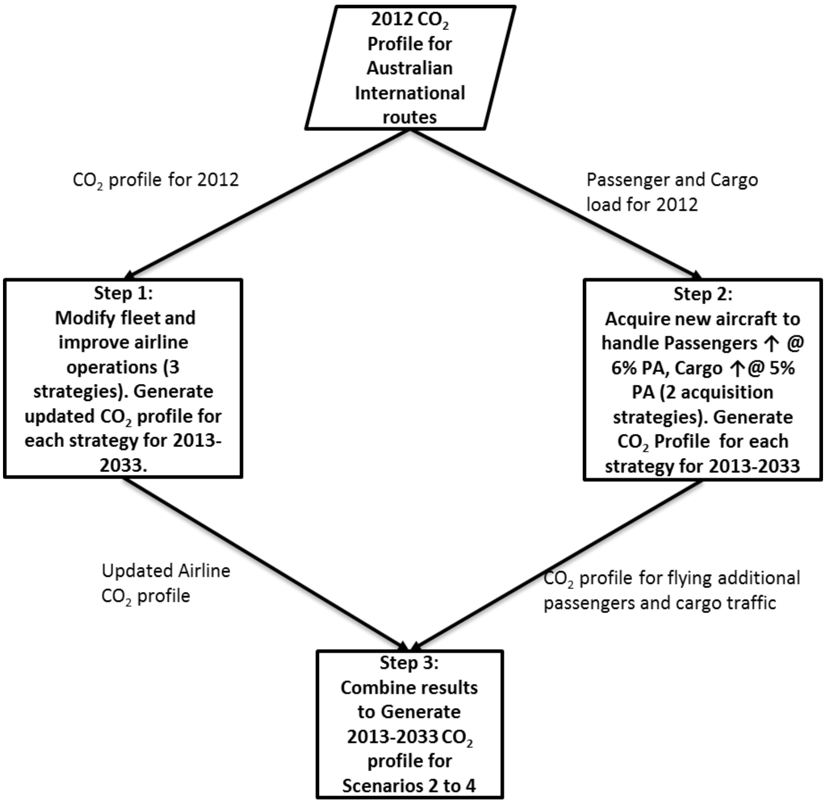

Figure 5.1 Generate CO2 profiles

5.3.1 Modifying fleet and improving airline operations (Step 1)

In Step 1, three strategies for modifying the fleet and improving airline operations were studied. Abatement options are applied to as many of the 2012 fleet as possible to determine the maximum amount of emissions saved. In 2014, Alaska Airlines retrofitted 73 737s with lightweight seats and 47 737s with scimitar winglets in 10 months (Alaska Airlines, 2014). Even though the planes deployed on Australian international routes in 2012 are mainly twin aisle aircraft, the model assumes that each airline can retrofit and modify their entire fleet that service Australian international routes in one year. For each strategy, the model was rerun to determine the annual CO_2 emitted from 2013 to 2033.

In the first strategy, abatement options in Table 5.1 and Table 5.2 were applied to the current fleet starting in 2013. Jetstar and Air New Zealand received their first A320 with Sharklets in the middle 2013 (Australian Aviation, 2013a, 2013b). Hawaiian Airlines and Air New Zealand installed winglets on their 767s to improve fuel efficiency in 2013 (Flightglobal, 2009; Kuhn, 2009). In this strategy, all 767s are retrofitted with winglets in 2013 and all 737NGs and A320s have winglets and Sharklets retrofitted a year later in 2014.

Airline’s fleet renewal plans are closely guarded secret but most have to take into consideration at least the aircraft’s age, maintenance cost, fuel efficiency, fuel cost, lease conditions, passenger traffic, current fleet composition, availability of new aircraft, cost of new aircraft and profitability. According to Morrell and Dray (2009), the age where 50% of both wide and narrow body aircraft has retired is 29.3 and 29.8 years respectively. Bazargan and Hartman (2012) modelled and analysed the aircraft replacement strategy for both low-cost carrier Air Tran Airways and legacy carrier Continental Airlines, they recommended selling aircraft at 12 years and older. In Table 5.13, airlines servicing the Australian international market in 2012 depreciated their fleet over a useful life of between 15 years for Singapore and Emirates to 30 years for United and Delta with most airlines depreciating their equipment between 20 to 25 years (Air New Zealand, 2012b; AirAsia, 2012; Cathay Pacific, 2012; Delta Air Lines, 2012; Emirates, 2012; Garuda, 2012; Malaysia Airlines, 2012; Qantas, 2012a; Singapore Airlines, 2012; United Airlines, 2012). The useful life usually indicates how long an airline keeps their aircraft before renewal.

In the second strategy, some of the oldest aircraft flown in 2012 were renewed in addition to the modifications and improvements introduced in the first strategy. Some of the oldest aircraft flown on long and medium haul Australian International routes were the 747-400s and 767s. Most non-Australian airlines replaced their 747-400s with 777s and the larger A380s. Singapore Airlines and Air New Zealand retired its last 747-400 in 2012 and 2014 respectively and Malaysia and United replaced their 747-400 service to Australia in 2013 and 2014 respectively using more efficient aircraft (Australian Aviation, 2012; Chong, 2014; Flynn, 2013). This leaves Qantas as the only airline flying 747-400s on Australian international flights after 2014. Qantas recently announced the purchase of 8 787-9s to replace 5 747-400s in 2017 and retired their last 767 in 2014 with A330s taking over the medium haul routes (Frawley, 2014a; Qantas, 2015). In this strategy, all non-Australian 747s were replaced by 777-300ERs in 2014 and all Qantas 747s were replaced by 787-9s in 2017.

In the third strategy, instead of modifying or updating the current fleet and airline operations as in the previous two strategies, the fleet renewal started in strategy 2 was greatly expanded. Some of the most utilised aircraft in short, medium and long haul were renewed with more efficient aircraft when they become available. In 2012, 40% of short haul routes were flown by 737NGs with another 30% flown by the A320s/A321s, over 70% of medium haul routes were flown on A330s and almost 40% of the long haul routes were flown by 777s and 29% by older 747s. Virgin Australia’s 737MAXs will be delivered in 2018, Jetstar’s A320NEOs will be delivered in 2017 and Emirates will upgrade their entire fleet of 777s to 777X starting from 2020. (Flynn, 2015a, 2015b; Frawley, 2014b; Qantas, 2015). Jetstar introduced the 787 on their medium haul international routes in 2014 (Qantas, 2013a). Even though some of the newer replacement aircraft can be configured with higher number of seats than the superseded aircraft, the model assumes the same seat count. Table 5.5

summarises the three strategies showing the year the current fleet were modified and renewed with new aircraft in the simulation.

Table 5.5. Timeline for operational changes and fleet modifications

Year	Strategy 1	Strategy 2	Strategy 3
2013	Perform 2-3 Engine washes per year Reduced Engine taxi Acquire iPad EFBs Install Lightweight IFE systems Install Lightweight seats Retrofit 767 winglets	Perform 2-3 Engine washes per year Reduced Engine taxi Acquire iPad EFBs Install Lightweight IFE systems Install Lightweight seats Retrofit 767s winglets	
2014	Retrofit 737NGs with scimitar winglets. Retrofit A320s with Sharklets.	Retrofit 737NGs with scimitar winglets. Retrofit A320s with Sharklets. Renew non-Australian airline 747-400s with 777-300ERs.	Renew A330s and 767s with 787s. Renew non-Australian airline 747-400s with 777-300ERs.
2017		Renew Qantas 747-400s with 787-9s.	Renew Qantas 747-400s with 787-9s.
2018			Renew 737NGs with 737MAXs. Renew A320s with A320NEOs.
2021			Renew 777-300ERs with 777Xs.

5.3.2 Acquiring new aircraft to service passenger and cargo growth (Step 2)

In Step 2, two aircraft acquisition strategies were studied. Airlines will add additional flights to handle the 6% growth in passengers and 5% growth in cargo per year from 2013 to 2033. Since the aircraft acquired will be similar to the aircraft used to renew the current fleet, the aircraft acquisition timeline will also be similar to the timeline in strategy 3 in Step 1. In 2012, international short, medium and long haul flights were on average 2944.27km, 6847.42km and 12210.29km long respectively where each passenger including their luggage (i.e. passenger-mass) weighed 110kg on twin-aisle flights and 100kg on single-aisle flights (Yin et al., 2015). The number of additional (short, medium and long haul) flights can be deduced by assuming that the proportion of short, medium and long haul passenger numbers and the passenger load factors on each flight remain unchanged from 2012. On each flight, total payload is the combined weight of passenger-mass and cargo, the additional cargo was divided evenly amongst these new flights. The model was then executed to determine the amount of CO_2 emissions and CO_2 efficiency associated with each aircraft acquisition strategy as passengers and cargo increased for each year starting from 2013 to 2033.

In the first strategy, airlines acquired and flew 737s/A320s, A330s and 777-300ERs to transport the additional passengers and cargo on short, medium and long haul flights respectively. These types of aircraft were selected because they accounted for the most Australian international short, medium and long haul flights in 2012. Since 737NGs/A320s, A330s and 777-300ERs were introduced prior to 2012, these aircraft flew the additional passengers and cargo from 2013 in this strategy. From 2014, 737NGs with scimitar winglets and A320s with Sharklets would fly all new short haul routes. Additional abatement options namely additional engine washes, reduced engine taxi, iPad EFBs, lightweight IFE systems, and lightweight seats were also applied to these aircraft.

In the second aircraft acquisition strategy, airlines flew some of the newest most efficient aircraft on short, medium and long haul flights. On short haul routes, 737NGs/A320s flew additional passengers and cargo starting from 2013, switching to the same aircraft with winglets in 2014 but from 2018 all additional passengers and cargo will be evenly split between A320NEOs and 737MAXs. On long haul routes, 777-300ERs are flown up to 2020 before switching to 777Xs from 2021. New aircraft introduced to handle passenger and cargo growth will not be renewed. For example, 777-300ERs introduced between 2013 and 2020 to cater to the growth in long haul traffic are not renewed with 777Xs after 2021 since they are only at most 8 years old. On medium haul routes, A330s will fly additional passengers and cargo in 2013 but from 2014 onward the additional passengers and cargo will be flown on 787s. Unlike the previous aircraft acquisition strategy, no other abatement options are applied to these aircraft. Table 5.6 summaries the two aircraft acquisition strategies showing the year new aircraft were acquired in the simulation.

Table 5.6 Timeline for Aircraft acquisition

Year	Strategy 1	Strategy 2
2013	Acquire 737NGs/A320s for short haul flights for 2013. Acquire A330s for medium haul flights from 2013 to 2033. Acquire 777-300ERs on long haul flights from 2013 to 2033 On these new aircraft Perform 2-3 Engine washes per yr Reduced Engine taxi Acquire iPad EFBs Install Lightweight IFE systems Install Lightweight seats	Acquire 737NGs/A320s for short haul flights for 2013. Acquire A330s for medium haul flights for 2013. Acquire 777-300ERs on long haul flights from 2013 to 2020.
2014	Acquire 737NGs with scimitar winglets and A320s with Sharklets for short haul flights from 2014 to 2033. On these new aircraft Perform 2-3 Engine washes per yr Reduced Engine taxi Acquire iPad EFBs Install Lightweight IFE systems Install Lightweight seats	Acquire 737NGs with scimitar winglets and A320s with Sharklets for short haul flights from 2014 to 2017. Acquire 787s instead of A330s for medium haul flights from 2014 to 2033.
2018		Acquire 737MAXs and A320NEOs instead of 737NGs/A320s for short haul flights from 2018 to 2033.
2021		Acquire 777Xs instead of 777-300ERs for long haul flights from 2021 to 2033.

5.3.3 CO_2 profile for 2012 to 2033 (Step 3)

The CO_2 profiles for scenarios 2 to 4 are made up of results generated in the previous two steps. Table 5.7 shows the fleet improvement strategy and the aircraft acquisition strategy used to produce the CO_2 profiles for Scenarios 2 to 4.

Table 5.7 Generate CO_2 profile for 2012 to 2033

	Scenario 2	Scenario 3	Scenario 4
Op changes & Fleet mods (Step 1)	Strategy 1 of Step 1	Strategy 2 of Step 1	Strategy 3 of Step 1
Aircraft acquisition (Step 2)	Strategy 1 of Step 2	Strategy 1 of Step 2	Strategy 2 of Step 2

5.3.4 Scenario 5 – Increasing payload per flight

In 2012, the average number of passengers per short, medium and long haul flight were 162.61, 260.26 and 309.24, the average number of seats were 213.07, 334.16 and 375.46 and passenger load factors were 76.3%, 77.9% and 82.4% respectively . In scenario 5, the number of seats per flight were unchanged but the average number of passengers per flight in scenarios 2 to 4 were increased by 5% and 10% thereby increasing passenger loading factors to (80.2%, 81.8%, 86.5%) and (83.9%, 85.7%, 90.6%) respectively. By increasing the number of passengers per flight, the number of flights required was reduced.

5.4 Results and Discussions

5.4.1 Modifying fleet and improving airline operations - Results (Step 1-Results)

Retrofitting the current fleet with emissions reduction technologies are limited to less than 5% saving according to Farries and Eyers (2008) and when all the abatement options in Table 5.1 and Table 5.2 are applied to the fleet flying on the 2012 Australian international routes, 400.2kt CO_2 emissions were reduced i.e. 3.05% saving (Table 5.8). The results from the model reflect the fidelity of fuel saving data associated with each abatement option. Due to a lack of detailed information on fuel savings from washing the aircraft engine, the model assumed a maximum savings of 1.2% for all flights. Whereas the more detailed fuel savings information associated with installing winglets on 767s, 737NGs and A320s and the smaller number of affected flights resulted in a relatively small combined savings of 0.25%.

Table 5.8 CO_2 savings due to operational changes and fleet modifications

Update operations and modify 2012 fleet	Airlines Affected	% CO_2 Saved	CO_2 Saved
Extra engine wash	Qantas, Virgin, Garuda, Malaysia, United, Air NZ, Hawaiian, Emirates, Etihad, Delta, Jetstar, Singapore, Cathay, AirAsia X	1.20%	157.3kt
Reduce engine taxi	Qantas, Virgin, Garuda, Malaysia, United, Air NZ, Hawaiian, Emirates, Etihad, Delta, Jetstar, Singapore, Cathay, AirAsia X	0.37%	48.2kt
iPad EFB	Qantas, Virgin, Garuda, Malaysia, United, Air NZ, Hawaiian, Emirates, Etihad, Delta, Jetstar, Singapore, Cathay, AirAsia X	0.01%	948.0t
Lightweight IFE system	Qantas, Virgin, Garuda, Malaysia, United, Air NZ, Hawaiian, Emirates, Etihad, Delta, Jetstar, Singapore, Cathay, AirAsia X	0.60%	78.3kt
Lightweight Seats	Qantas, Virgin, Garuda, Malaysia, United, Air NZ, Hawaiian, Emirates, Etihad, Delta, Jetstar, Singapore, Cathay, AirAsia X	0.63%	82.4kt
767 winglets	Air NZ, Hawaiian, Qantas	0.07%	9.2kt
A320 Sharklets	Air NZ, Jetstar	0.09%	12.3kt
737NG scimitar winglets	Qantas, Virgin, Garuda, Malaysia, United	0.09%	11.5kt

By 2014 non-Australian airlines stopped flying 747-400s to Australia; most have replaced these flights with newer aircraft like 777s, A380s and A330s. In the model, non-Australian 747 flights were replaced by 777-300ER flights; which resulted in a reduction of 203.6kt CO_2 emissions. Qantas announced the purchase of 787-9s to replace some of their 747-400s. If Qantas replaced their entire fleet of 747s with 787-9s, CO_2 emissions would be reduced by 410.6kt. If airlines flying in 2012 Australian international routes implemented the fleet renewal strategy 3 specified in Table 5.5, it resulted in CO_2 reduction of over 15%. Even though almost 60% of international flights were short haul and 70% of these flights were flown with 737NGs and A320s, it accounted for less than 20% of 2012 emissions so renewing to 737MAXs and A320NEOs respectively has a relatively small reduction of 159.78kt. Whereas medium and long haul flights accounted for the most emissions savings. Table 5.9 lists the maximum CO_2 emissions reduction when each aircraft type was renewed on 2012 Australian international routes.

Table 5.9 CO_2 savings due to fleet renewal strategy

Aircraft renewal	Airlines Affected	% CO_2 Saved	CO_2 Saved
777-300ERs replace 747-400s	Singapore, Air NZ, Malaysia, United	1.55%	203.6kt
787-9s replace 747-400/400ERs	Qantas	3.13%	410.6kt
787s replace 767s, A330s	AirAsia X, Air NZ, Malaysia, Hawaiian, Qantas, Jetstar, Cathay, Garuda	5.85%	767.2kt
A320NEOs replace A320/A321s	Jetstar, Air NZ	0.54%	71.1kt
737MAXs replace 737NGs	Qantas, Virgin, Garuda, Malaysia, United	0.68%	88.6kt
777Xs replace 777-300ERs	Singapore, Air NZ, Malaysia, United, Virgin	5.02%	658.3kt

5.4.2 Acquiring new aircraft to service passenger and cargo growth – Results (Step 2-Results)

In 2012, 14 airlines transported 21.4M international passengers and 611.5Mkg of cargo into and out of Australia (Yin et al., 2015). Figure 5.2 shows the 6% and 5% per annum growth in additional passengers and cargo from 2013 to 2033, with passengers accounting for just over 80% of the additional payload weight.

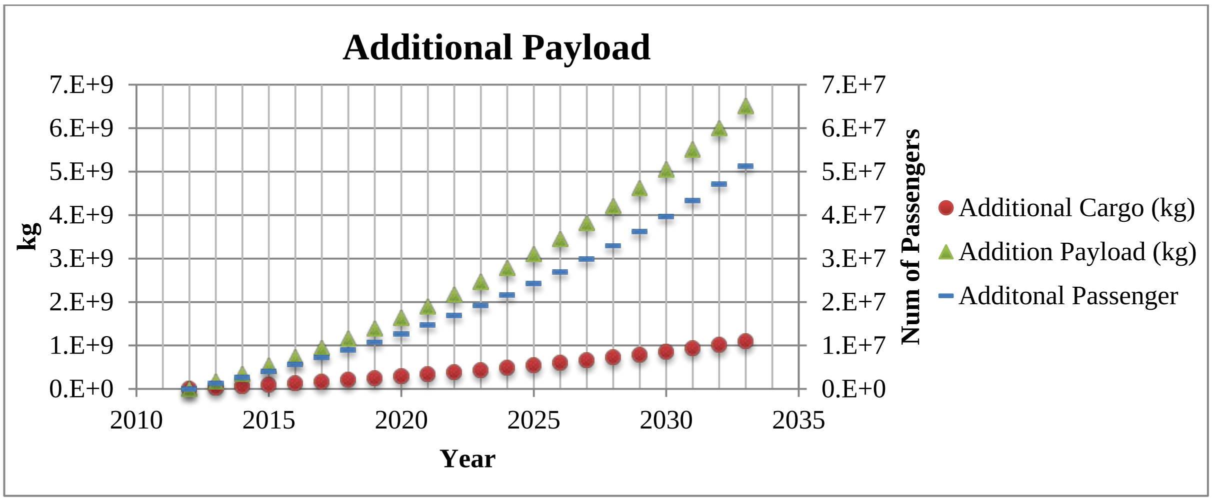

Figure 5.2.Passengers and cargo growth

To cater to this growth, the model assumed that airlines will purchase or lease new aircraft for short, medium and long haul flights. The results for the two aircraft acquisition strategies (Table 5.6) and the BAU case, where each airline transported the additional passengers and cargo at the same CO_2 efficiency as in 2012 are presented in Figure 5.3. In the first aircraft acquisition strategy, 24.1Mt of CO_2 was emitted in 2033, a saving of 5.7Mt when compared to BAU case. In the second aircraft acquisition strategy, flying the newest aircraft instead of just the most utilised aircraft from 2012 saved an additional 3.1Mt of CO_2 by 2033.

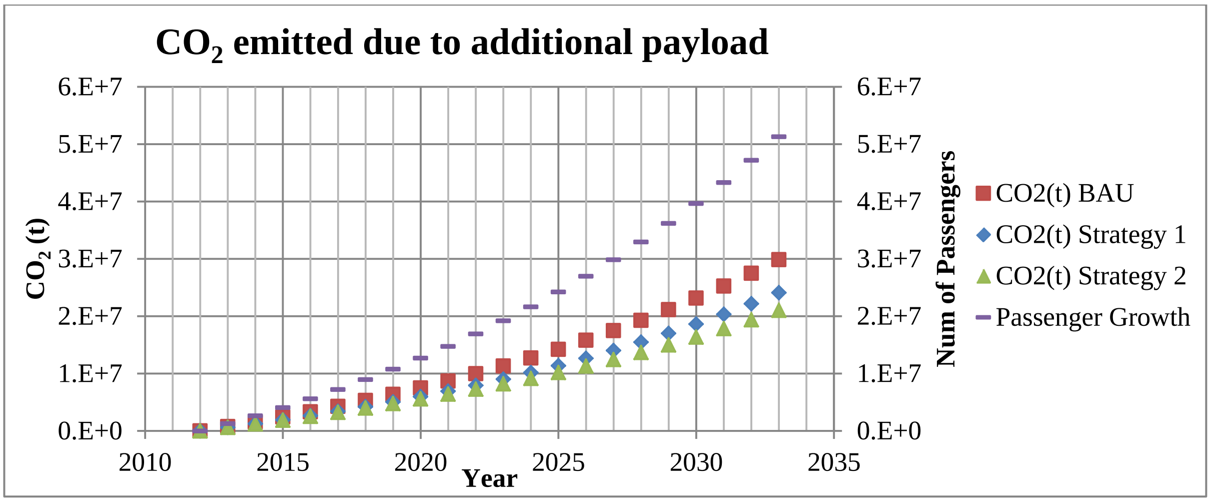

Figure 5.3. CO_2 Emission due to additional passengers and cargo

5.4.3 CO_2 profile for 2012 to 2033 (Step3-Results)

In 2012, 13.1Mt of CO_2 was emitted by 14 airlines flying in the Australian international aviation market. These airline emitted CO_2 at a rate of between 64.78g of CO_2 per passenger-km to 117.28g of CO_2 per passenger-km (0.59g of CO_2 per kg of payload-km to 1.07g of CO_2 per kg of payload-km) (Yin et al., 2015). With annual passenger and cargo traffic increasing at 6% and 5% respectively, total passenger numbers and cargo will double by 2024 and 2026 respectively. Figure 5.4 shows the amount of CO_2 emitted from 2012 to 2033 for scenarios 1 to 4. In scenario 1 (i.e. BAU), if each airline operated with no improvements to their CO_2 emissions efficiency, then CO_2 emissions will double by 2025 and by 2033 will reach 42.9Mt. In scenario 2, 2012 fleet was updated with a number of operational changes and fleet modifications plus the increase in passenger and cargo traffic from 2013 to 2033 will be serviced by 737NGs/A320s, A330s, and 777-300ERs for short, medium and long haul flights. In this scenario, CO_2 emissions will double by 2027 and by 2033 will reach 36.8Mt. Scenario 3 is similar to scenario 2, but 747s were renewed with 777-300ERs and 787-9s. In this scenario, renewing 747s resulted in an additional 4.69% reduction in CO_2 emissions from the 2012 flights. Since the only difference between scenario 2 and 3 was the renewal of 747s there was only a small drop in CO_2 of 614.23kt in 2033 with CO_2 emissions doubling by 2028. Both scenarios showed that a more aggressive strategy is needed to curb the increase in emissions due to traffic growth. In scenario 4, airlines deployed the latest aircraft for all new passenger and cargo traffic and also extensively renewed their current fleet. By 2033, CO_2 emissions dropped to 32.1Mt where over 80% of all long haul flights will be flown on 777s and over 90% of medium and short haul flights will be flown on 787s and 737MAXs/A320NEOs respectively. This resulted in an additional saving of 4.04Mt of CO_2 emissions by 2033, but CO_2 emissions will double by 2030. For airlines to stay carbon neutral after 2020, an additional 15.98Mt of CO_2 emissions will need to be reduced.

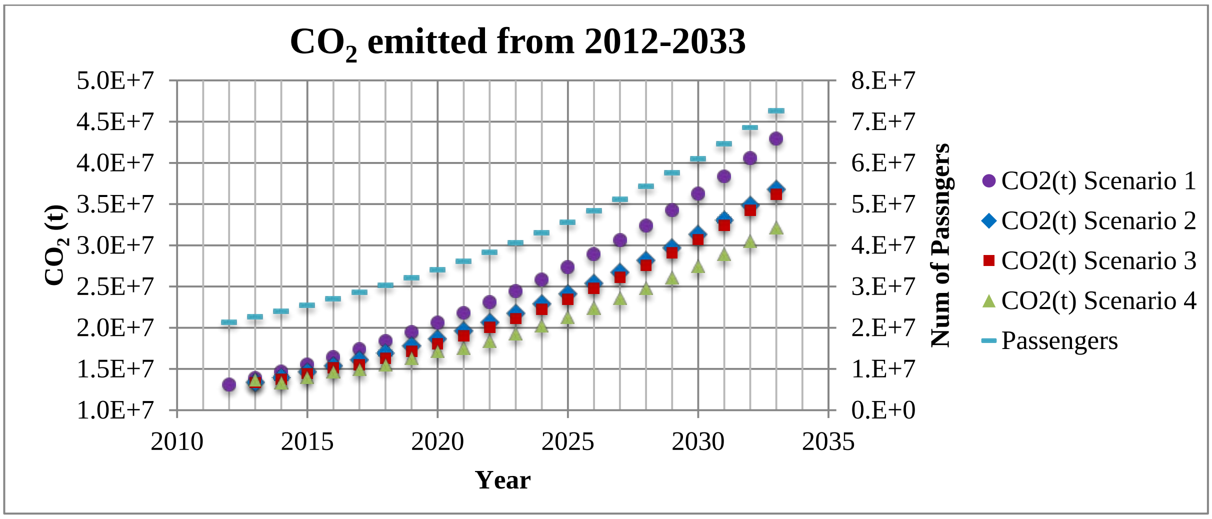

Figure 5.4. CO_2 Emissions from 2012 to 2033

In Figure 5.5, flying more-efficient aircraft helped to improve the average CO_2 efficiency from 75.68g of CO_2 per passenger-km (0.71g of CO_2 per kg of payload-km) in 2012 to 53.81g of CO_2 per passenger-km (0.51g of CO_2 per kg of payload-km) in 2033 in scenario 4 while carrying more than triple the number of passengers. In 2012, AirAsia X had the best CO_2 efficiency of 64.86g of CO_2 per passenger-km (0.59g of CO_2 per kg of payload-km); CO_2 efficiency for all flights in scenario 2, 3 and 4 matched AirAsia X's efficiency by 2024, 2020 and 2017 respectively (Yin et al., 2015).

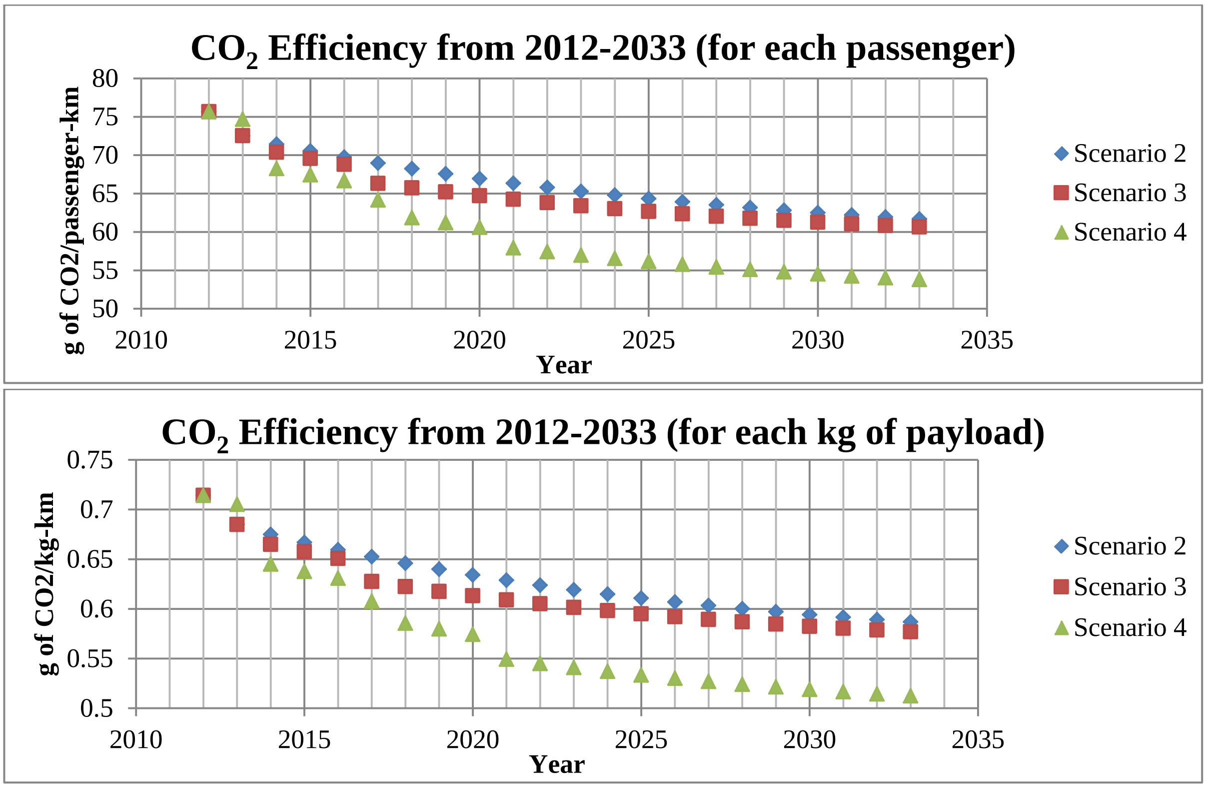

Figure 5.5. CO_2 Efficiency from 2012 to 2033

5.4.4 Scenario 5 - Increasing number of passengers per flight

In scenario 1 to 4, the average number of passengers and seats on each short, medium and long haul flight remain unchanged from 2012. In scenario 5, the passenger numbers on each flight in scenario 2 to 4 were increased, thereby reducing the number of flights required to transport the same number of passengers and cargo for each year. By increasing the number of passengers per flight by 10% an additional 9% of CO_2 emissions were reduced (Table 5.10).

Table 5.10. CO_2 profile for higher load factors

		Scenario 2			Scenario 3			Scenario 4		
		Increase pax/flight by			Increase pax/flight by			Increase pax/flight by		
Year	CO_2	0%	5%	10%	0%	5%	10%	0%	5%	10%
2020	Mt	18.7	17.8	17	18.1	17.2	16.4	17.2	16.3	15.6
	g/pax-km	66.94	66.17	65.53	64.72	63.91	63.23	60.62	59.94	59.38
	g/kg-km	0.63	0.63	0.62	0.61	0.60	0.60	0.57	0.57	0.56
2033	Mt	36.8	35.0	33.4	36.2	34.5	32.9	32.1	30.6	29.2
	g/pax-km	61.7	59.99	58.49	60.66	58.91	57.38	53.81	52.32	51.02
	g/kg-km	0.59	0.57	0.56	0.58	0.56	0.54	0.51	0.50	0.49

In the BAU scenario, CO_2 grew at over 11% per annum and by 2033 CO_2 emissions has increased to 42.9Mt. By applying an aggressive fleet acquisition and renewal strategy and increasing the number of passengers per flight by 10%, the results showed that CO_2 emissions growing at 6.1% per annum and CO_2 per passenger-km drops from 75.68g/pax-km in 2012 to 51.02g/pax-km in 2033. Even though CO_2 emissions are down to 29.2Mt, an additional 13.6Mt of CO_2 needs to be trimmed from the Australian international flights to stay carbon neutral after 2020. These results also show a higher emission growth than the Australian Government's 2.9% per annum and this is attributed to the Australian Government's study using a lower passenger growth rate of 4% per annum and higher yearly drop of 2.3% in CO_2 emitted per international passenger (Commonwealth of Australia, 2012).

These results show that due to the growth in passengers and cargo, airlines have to attain an even higher drop in CO_2 emitted per passenger-km (CO_2 emitted per kg of payload-km) in order to achieve carbon neutral growth after 2020.

Addendum:

In Scenario 5, the model does not factor in the additional fuel required to fly more passengers and freight when the load factor is increased by 5% and 10% on each flight. In Table 5.11 and Table 5.12, the percentage of fuel saved when the weight of a 737NG, A330 and 777 is decreased by 1000 lbs (454 kg) is 0.6%, 0.18% and 0.2%, respectively. Assuming a similar increase in fuel used when weight is increased, a 10% load factor increase on a 737NG, A330 and 777 equates to a weight increase of approximately 1990 kg, 3840 kg and 4500 kg, respectively, which translates to 2.6%, 1.5% and 2.0% increase in fuel/emissions.

If the increase in fuel used/emissions on each flight is factored in when load factors are increased by 5% and 10% then by 2033 total emissions will drop by 3.9% and 7.4% instead of 4.7% and 9.1% that is presented in Table 5.10 and in Yin et al. (2016).

5.5 Conclusions

Airlines can modify their current operations, retrofit their fleet of aircraft with emissions reducing technologies, retire inefficient aircraft and acquire more efficient aircraft to reduce their emissions. To determine fuel savings for each abatement option, the fuel burn tables in CO_2 profile calculator used to determine the 2012 CO_2 profile for the Australian International Market was modified. From 2013 to 2033, passenger and cargo traffic will increase at 6% and 5% per annum respectively and the model assumes that airlines will add additional flights on top of their 2012 flight schedule. Assuming airlines maintain their 2012 flight schedule, the CO_2 emissions from 2013 to 2033 is the combination of emissions from 2012 flight schedules and emissions generated from flying the additional passengers and cargo. To determine the CO_2 emissions due to the additional traffic, the model assumes the average short, medium and long haul flight distance and number of seats per flight remained the same as in 2012. The aircraft chosen to service the additional passenger and cargo traffic ranged from the most utilised aircraft type in 2012 such as 737NGs, A320s, A330s and 777s to some of the latest aircraft introduced after 2012 such as the 737MAXs, A320NEOs, 787s and 777Xs.

Five scenarios were studied with various abatement mitigation strategies, to determine the growth in CO_2 emissions as passenger and cargo increased from 2013 to 2033. As expected, increasing the number of passengers per flight by 10%, applying an aggressive fleet renewal strategy by replacing the current fleet with the latest aircraft and adding the latest most efficient aircraft to service the additional traffic would reduce CO_2 emissions growth to 6.1% per annum and produce the most CO_2 emissions reduction when compared to the other scenarios. The results showed that airlines will need additional abatement options such as implementing more operational changes, acquiring new technologies, refuelling with 2nd and 3rd generation biofuels, implementing some Market Based Measures (MBM) and behavioural changes in order to reduce an additional 13.6Mt from the 29.2Mt of CO_2 (in 2033) to stay carbon neutral after 2020.

The adoption of any abatement option is highly dependent on cost and ease of implementation, fuel prices and economic growth. The pricing of CO_2 emissions and penalising poor CO_2 efficiency and low load factor should be investigated to determine if it would increase the uptake of these abatement options. Additional research should be undertaken to facilitate the production of aviation biofuel, to improve airport infrastructure and air traffic management and to discourage unnecessary air travel.

5.6 Supplementary data

Table 5.11 summarises the amount of fuel saved for each 1000lb/454kg reduction in weight for the following Boeing aircraft (Boeing, 2004).

Table 5.11. Fuel Saved on Boeing Aircraft

Aircraft type	Fuel save per 1000lb (454 kg) decrease in weight (%)
737-6/7/8/900	0.6%
767-2/3/400	0.3%
777-2/300	0.2%
747-400	0.2%

Table 5.12 summarises the fuel penalty in a typical sector for Airbus aircraft (Airbus, 2004).

Table 5.12. Fuel Saved on Airbus Aircraft

Aircraft type	Typical Sector (nm)	Fuel burn in Typical Sector from updated CORINAIR fuel burn table (kg)	Weight Increase (kg)	Fuel Penalty per sector (kg)	Fuel saved per 1000lb (454 kg) decrease in weight (%)
A320	1000	6280.37	735	60	0.59% =454/735 *60/6280.37
A321	1000	7272.67	890	55	0.39% =454/890*55/7272.67
A330-200	4000	51005.69	2300	460	0.18% =454/2300*460/51005.69
A330-300	4000	51005.69	2300	440	0.17% =454/2300*440/51005.69
A340-300	6000	113821.10	2535	1330	0.21% =454/2535*1330/113821.1
A340-500	6000	113821.1	3680	1410	0.15% =454/3680)*1410/113821.1
A340-600	6000	113821.1	3660	1420	0.15% =454/3660*1420/113821.1

Since there is no data for the A380, in the model the fuel savings is assumed to be similar to the 747 at 0.2%.

Table 5.13. Airline depreciation

Airline	Useful Life (years)	Annual Depreciation rate (%)	Residual value (%)	Reference
Qantas/Jetstar	2.5-20	Not disclosed	0-10	(Qantas, 2012a)
Virgin	Not disclosed	5-25	Not disclosed	(Virgin Australia, 2012a)
Air NZ	5-22	Not disclosed	Not disclosed	(Air New Zealand, 2012b)
AirAsia X	25	Not disclosed	10	(AirAsia, 2012)
Cathay	20	Not disclosed	10	(Cathay Pacific, 2012)
Delta	21-30	Not disclosed	5-10	(Delta Air Lines, 2012)
Emirates	15	Not disclosed	10	(Emirates, 2012)
Etihad	Not disclosed	Not disclosed	Not disclosed	(Etihad, 2012)
Garuda	18-20	Not disclosed	Not disclosed	(Garuda, 2012)
Malaysia	20	Not disclosed	Not disclosed	(Malaysia Airlines, 2012)
Singapore	15	Not disclosed	10	(Singapore Airlines, 2012)
United	27-30	Not disclosed	Not disclosed	(United Airlines, 2012)
Hawaiian	20-25	Not disclosed	0-10	(Hawaiian Airlines, 2012)

Chapter 6. The cost of abatement options to reduce carbon emissions from Australian international flights

Yin K-s, Ward A, Dargusch P, Halog A. (2016). The cost of abatement options to reduce carbon emissions from Australian international flights. (Under review at *International Journal of Sustainable Transportation*)

Chapter Summary

In 2012, a total of 13.1 million tonnes of carbon dioxide were emitted by 14 airlines when transporting 72 per cent of international passengers into and out of Australia in 2012. With passenger and cargo traffic growing at between five to six per cent annually from 2013 to 2033, acquiring more fuel efficient aircraft to both renew the existing fleet and to service growth have the greatest potential in reducing emissions over the next 20 years. The analysis shows that implementing carbon dioxide emissions abatement options such as installing light weight seats, iPad electronic flight bags, winglets, washing aircraft engines and reducing the number of engines used during taxiing, all offer net financial savings when considered over 20 years. Acquiring new fuel efficient aircraft has the biggest impact on emissions reduction. Low interest loans and longer loan repayment periods may incentivise airlines to acquire more fuel efficient aircraft to service traffic growth but other complimentary incentives and penalties are required to influence airlines to replace their current fleet with more fuel efficient aircraft.

6.1 Introduction

In 2012, 13.1 million tonnes of carbon dioxide (Mt CO_2) was emitted by 14 airlines flying 21.4 million international passengers into and out of Australia. Long and medium haul flights account for forty per cent of all international flights and eighty per cent of these emissions. Australia-based Qantas, Jetstar and Virgin Australia airlines accounted for just over a third of these emissions (Yin et al., 2015). According to Airbus and Boeing, passenger and cargo traffic are expected to grow at between five to six per cent annually from 2013 to 2033 (Airbus, 2012b; Boeing, 2012b). This increase in traffic will drive CO_2 emissions up to 43Mt. However, by implementing a number of abatement strategies, emissions growth can be reduced to between 32.1Mt to 36.8Mt of CO_2 where each strategy is a combination of a number of abatement options (Yin et al., 2016). The cost at which these abatement strategies are likely to be implemented was not specified; rather, Yin et al recommended that applying these strategies could broadly include modifying the current fleet, changing current operations and renewing and adding newer more efficient aircraft to the fleet from 2013 to 2033 (Yin et al., 2016).

This chapter builds on Chapter 5 (and Yin et al. (2016)) and provide the marginal abatement cost for each abatement option. Here marginal abatement cost refers to abatement cost for each tonne of carbon dioxide saved estimated out to 2033 when compared against a baseline reference scenario where airlines retire and renew their current fleet at 25 years old. The results are presented graphically as Marginal Abatement Cost Curves (MACCs) that show the cost in US dollars per tonne of CO_2 saved (US$/t$CO_2$) and the total possible volume abated for each abatement option. MACCs aim to assist managers in identifying, ranking and prioritising the emission abatement options based on cost per tonne of carbon dioxide saved.

Marginal abatement cost for both domestic and international aviation in other regions like European Union (EU) and countries such as the United Kingdom (UK) have being produced in studies by Holland et al. and Morris et al. (Holland et al., 2011; Morris, Rowbotham, Angus, Mann, & Pol, 2009; Morris, Rowbotham, Morrell, et al., 2009). The objective of this chapter is to rank and prioritise the abatement options for each Australia-based airline, all non-Australia-based airline flights, and all the new aircraft that will service passenger traffic growth and determine if favourable loan terms will increase the likelihood that airlines will renew and acquire new aircraft. The results show that some of these abatement options in Chapter 5 (and Yin et al. (2016)) are not financially viable due to the high implementation cost and low savings in fuel and maintenance cost. Reducing the interest rate and extending the repayment period on loans on new aircraft can influence airlines in purchasing the latest most fuel efficient aircraft to service traffic growth. But this might not be enough to convince airlines to replace an aircraft in their fleet with one that is more fuel efficient.

Our results show that if airlines implement only the financially viable abatement options where purchased aircraft are financed at six per cent and repaid over 12 years, CO_2 emissions will be reduced to 33.6Mt in 2033. By decreasing interest rate to two per cent, additional abatement options become financially viable and CO_2 emissions drop to 31.7Mt in 2033. This is lower than the 32.1Mt specified in Chapter 5 (and Yin et al. (2016)) which involved acquiring new aircraft to renew the current fleet and to service the growth.

The chapter is organised as follows. Section 6.2 provides a review of the emissions calculator used in Chapter 4 (and Yin et al. (2015)), abatement options presented in Chapter 5 (and Yin et al. (2016)) and the associated fuel saved and marginal abatement cost. A description of how MACCs were produced for both Australian and non-Australian flights out to 2033. Capital cost of abatement options, winglets list price, new aircraft list price, aircraft lease rates, aircraft maintenance cost, fuel price and inflation rate are also listed. The aircraft financing and recurring cost are also presented in this section. This cost data was used to produce the MACCs. Section 6.3 provides a description of the reference scenario used in the MACC. This section will estimate the number of aircraft and the average age of current fleet; and the number of aircraft servicing the growth in passenger and cargo to 2033. In Section 6.4, MACCs for all three Australian airlines, all non-Australian aircraft and aircraft acquired to transport the traffic growth are presented. Results will include sensitivity to interest rate and repayment period changes. Finally, conclusions are presented in Section 6.5.

6.2 Methods

6.2.1 Emission calculator

In 2012, 13.1Mt of CO_2 emissions was generated on Australian international routes transporting 21.4million passengers and 1.68 MT freight (Yin et al., 2015). This was estimated using a carbon calculator that was based on the ICAO Carbon Calculator with modified Core Inventory of Air Emission (CORINAIR) fuel burn tables and does not take into consideration class of travel (European Environment Agency, 2006; Horton, 2010; ICAO, 2014b; Yin et al., 2015). The modified CORINAIR fuel burn tables are more accurate and has additional fuel burn tables for newer aircraft (European Environment Agency, 2006; Horton, 2010). The calculator assumes that aircraft will fly the great circle distance route between airports and to account for air traffic congestion an additional 50km to 125km was added to distance flown (ICAO, 2014b). Payload is made up of the weight of passengers, luggage and freight where the average passenger weight is 85 kg with luggage of 15 kg on single isle aircraft that are used mainly on short haul international flight and 25 kg on twin aisle aircraft. Qantas was the largest emitter and AirAsia X and Cathay Pacific were two of the most CO_2 efficient airlines while flying identical aircraft types to and from Australia in 2012 (Yin et al., 2015). Low cost carrier AirAsia X achieved a CO_2 efficiency of 0.59 grams (g) of CO_2 for each kilogram (kg) of payload transported over a kilometre (km) by carrying more passengers whereas the traditional network carrier Cathay Pacific achieved a CO_2 efficiency of 0.6 grams of CO_2 for each kilogram of payload transported over a kilometre by carrying more freight on each flight (Yin et al., 2015).

6.2.2 Abatement options

Over the next 20 years, passenger and freight traffic in the Asia-Pacific region are expected to grow at an annual rate of six and five percent respectively and CO_2 emissions will reach 42.9Mt by 2033 (Airbus, 2014b; Boeing, 2014b; Yin et al., 2016).

Abatement options that are available for reducing CO_2 emissions in the aviation-airline industry may include changes to aircraft operations; improvements to infrastructure; acquiring aviation technologies to improve efficiency; refuelling with alternative fuels and behavioural changes (Banbury, Behrens, Bowell, et al., 2009; Banbury, Behrens, Browell, et al., 2009; Braathen et al., 2012; Commonwealth of Australia, 2012; L. M. Dray et al., 2009; Farries & Eyers, 2008; Green et al., 2005; Holland et al., 2011; Kar et al., 2010; Morris, Rowbotham, Morrell, et al., 2009; Sustainable Aviation, 2012). Australia based airlines have announced plans to implement or have implemented a number of abatement options which were specified in their Energy Efficiency Report to the Australian Government's Department of Resource, Energy and Tourism (Qantas, 2011, 2012b, 2013b; Virgin Australia, 2011, 2012b, 2013b).

Yin et al. (2016) have shown that by implementing a limited number of abatement options that have minimal dependence on other stakeholders including options from the Energy Efficiency Report, airlines flying on Australian international routes can reduce CO_2 emissions to 32.1Mt by 2033. These abatements options and associated fuel and weight savings are summarised in Table 6.1 and the amount fuel saved for each 1000lbs reduction are summarised in Table 6.2 (Airbus, 2004; Boeing, 2004; Yin et al., 2016):

Table 6.1 Abatement options and associated fuel and weight saved

Abatement option	Fuel and weight saved
Engine Wash	1.2%
Reduce Engine Taxi	20% during taxi phase
Lightweight Seats	4kg/seat
iPad Electronic Flight Bag	14.65kg/iPad
Lightweight IFE	3.8kg/seat
737NG scimitar winglets	1.0 to 2.2%
767-300 winglets	3.0 to 5.7%
A320 Sharklets	2.5 to 3.5%
777X	16% compared to 777-300ER
777-300ER	17-25% compared to 747
787-9	30% compared to 747
787-8	20% compared to 767
737MAX	14% compared to 737NG
A320NEO	15% compared A320

Table 6.2 Fuel saved due to weight reduction

Aircraft type	Fuel saved per 1000lbs (454kg) weight reduction
737NG	0.6%
767	0.3%
777-200/300	0.2%
747-400	0.2%
A320	0.59%
A321	0.39%
A330-200	0.18%
A330-300	0.17%
A340-300	0.21%
A340-500	0.15%
A340-600	0.15%

6.2.3 Marginal Abatement Cost

This chapter determines the marginal cost of each abatement options presented in Table 6.1. The marginal abatement cost will be graphically presented in Marginal Abatement Cost Curves.

Marginal abatement cost presents the cost of additional emissions reduction associated with each abatement option under consideration when compared to a reference scenario. Marginal abatement cost for abatement option *i* in year *y* is:

$$\frac{cost_{i,y} - cost_{ref,y}}{CO2_{ref,y} - CO2_{i,y}} \qquad (1)$$

where

$cost_{i,y}$ is the total cost for abatement option *i* in year *y*

$cost_{ref,y}$ is the total cost for the reference scenario in year *y*

$CO2_{i,y}$ is the amount of CO_2 generated for abatement option *i* in year *y*

$CO2_{ref,y}$ is the amount of CO_2 generated for the reference scenario in year *y*.

A negative marginal abatement cost (equation (1) represents cost savings when compared to the reference scenario for each unit of CO_2 emissions reduction in year *y*.

To determine the cost effectiveness of abatement option *i* over the next N years, calculate the difference between the Net Present Value (NPV) for abatement option *i* and the NPV of the reference scenario divided by the amount of CO_2 saved i.e.

$$\frac{NPV_i - NPV_{ref}}{CO2_{ref} - CO2_i}$$

(2)

where

$$CO2_i = \sum_{y=y_1}^{y_N} CO2_{i,y}$$

$$CO2_{ref} = \sum_{y=y_1}^{y_N} CO2_{ref,y}$$

$$NPV_i = \sum_{y=y_1}^{y_N} \frac{cost_{i,y}}{(1 + discoutRate)^{(y-y_o)}}$$

$$NPV_{ref} = \sum_{y=y_1}^{y_N} \frac{cost_{ref,y}}{(1 + discountRate)^{(y-y_o)}}$$

discountRate is the weighted average cost of capital (WACC).

Between 2004 to 2011, the WACC was 7.7 per cent for both low cost and network carriers flying in the Asia Pacific region (B. Pearce, 2013).

In this chapter, $cost_{i,y}$ will include the cost of the acquisition which can be a lease or loan, maintenance, fuel, aircraft disposal and depreciation. $CO2_{i,y}$ is the CO_2 emissions generated from the simulations of each abatement option using the model in Yin et al. (2016). In the model, the yearly discount rate is set to 7.7 per cent.

6.2.4 Marginal Abatement Cost Curves

MACCs have been used to graphically present marginal cost of abatement options for industries such as power generation, farming, to tree planting in New York City and aviation (Bockel, Sutter, Touchemoulin, & Jönsson, 2012; Hamamoto, 2013; Holland et al., 2011; Kovacs, Haight, Jung, Locke, & O'Neil-Dunne, 2013; Moran et al., 2011; Morris, Rowbotham, Angus, et al., 2009).

There are two different graphical representations of MACCs namely as a histogram or curve. In this chapter, MACC histograms illustrate the impact of each CO_2 emission abatement option where each option is ranked according to its marginal abatement cost i.e. the amount spent or saved for each tonne of CO_2 abated. Options are ordered from left to right representing the lowest cost per unit CO_2 save to the highest. A negative marginal abatement cost (below horizontal axis) represents financial savings even after spending the cost of implementing the abatement option, and vice versa for a positive cost (above horizontal axis) when compared to the reference scenario. The total CO_2 abated by each option is represented by the width along the horizontal axis in the MACC.

6.2.5 Cost of abatement options for existing aircraft fleet

The cost of modifying the existing fleet with new equipment such as light weight aircraft seats, Inflight Entertainment systems (IFEs) and Electronic Flight Bags (EFBs) depends on the manufacturer selected. All equipment manufacturers contacted by the authors would not divulge their product prices and airlines were unable to disclose the actual price paid due to confidentially agreements. As such, the costing information used in the model was collected from press releases, magazine articles, trade publications and manufacturer's websites.

In 2012, Southwest Airlines retrofitted 372 737-700s with 143 light weight seats on each plane at a cost of US$110m i.e. US$2,068/seat (Maxon, 2012). Spirit airlines purchased 5,000 slim lightweight Acro seats at a cost of US$9.9m in 2014 i.e. US$1,980/seat (Kirby, 2014). IFEs in the 1990 cost US$1,800 per seat but by 1999 this had increase to US$10,000 per seat (Alamdari, 1999). IFEs installed on Emirates aircraft can cost between US$10,000 to US$15,000 per seat (ifenews, 2012; Trejos, 2013). Lumexis claims their IFEs are half the cost of typical IFE systems. (Aircraft Interior International, 2013). According to Mckenna (2013) iPad EFBs cost US$499 per unit with two tablets per plane.

There are many companies that offer aircraft engine washing services and just like equipment manufacturers the cost is not published. According to Jet Fuel Intelligence (2009), engine washing cost about US$3,000 per wash with an aircraft requiring two to three washes per year. The cost will vary depending on the aircraft type and usage. Airlines will receive discounts on large winglet orders but this information is not publicly available (Aviation Partners Boeing, 2015; Wall, Norris, Anselmo, & Flottau, 2011). Reducing the number of engines used during taxiing will require additional training for pilots but no new equipment will be purchased. It's unclear what this additional training cost will be or if there will be additional maintenance cost on the engines.

Table 6.3 summaries the costs associated with the eight abatement options identified in Chapter 5 (Yin et al. (2016)). The costs of these abatement options are adjusted at the rate of inflation over the simulation period of 2013 to 2033.

Table 6.3 Capital cost of abatement options

Abatement option	Year	Cost (US$)
Engine Wash (cost per wash)	2009	US$3,000
Reduce Engine taxi	NA	US$NIL
Lightweight seat (cost per seat)	2014	US$2,000
Lightweight IFE (cost per seat)	2012	US$7,500
iPad EFB (2x$500 per plane)	2012	US$1,000
737NG Scimitar winglets (cost per plane)	2015	US$575,000
767 winglets (cost per plane)	2015	US$2,400,000
A320 Sharklets (cost per plane)	2011	US$950,000

6.2.5.1 Recurring cost

Companies tend to replace their laptop PCs more often due to the abuse they receive. The average life cycle of laptop is three years and desktop is four years but this can vary depending on the size of company and how often the systems and software are updated (Garretson, 2010). Since there are no guidelines on how often the iPad EFBs are to be replaced, the model assumes a three years renewal cycle with the cost of iPads adjusted at the rate of inflation.

Aircraft seats and IFEs will need to be replaced due to obsolescence; and wear and tear. They are usually refurbished together when airlines perform major interior upgrade during major aircraft maintenance checks such as D-checks which occurs approximately after six years of flying (Lufthansa Technik, 2016). Virgin Australia refurbished their 777s after seven years whereas Air New Zealand 777s were refurbished at nine years (Air New Zealand, 2012a; Thomas, 2014). In the model, seats and IFEs are refurbished every seven years and costs are adjusted at the rate of inflation.

As technology improves seats, IFEs and tablet computers may get lighter but in the model the weight savings are factored in only once during the initial upgrade and all subsequent refurbishment will not achieve any additional weight savings. Maintenance cost on seats, IFEs and iPads are not included in the model.

6.2.6 Cost of new fuel efficient aircraft

Airlines can reduce their emissions by acquiring new more fuel efficient aircraft. There are many ways in which an airline can acquire new aircraft. This can range from paying cash, obtaining a loan with some of these loans guaranteed by government credit agencies or leasing (Reuters, 2012). The published prices in Table 6.4 for both Airbus and Boeing aircraft have increased by approximately three per cent per annum (Airbus, 2013, 2014c, 2015; Boeing, 2015). Most airlines and aircraft leasing companies receive discounts of up to 60 per cent on the list price based on the volume of their order but the actual price paid are rarely published (Michaels, 2012).

In the model, aircraft list price is assumed to increase at a rate of three per cent annually from 2015 to 2033.

Table 6.4 Aircraft list price (in millions US$)

Aircraft type	2013	2014	2015
A320	$91.5m	$93.9m	$97.0m
A320NEO	$100.2m	$102.8m	$106.2m
A330-200	$216.1m	$221.7m	$229.0m
A330-300	$239.4m	$245.6m	$253.7m
737-800	$90.5m	$93.3m	$96.0m
737MAX8		$106.9m	$110.0m
787-8	$211.8m	$218.3m	$224.6m
787-9		$257.1m	$264.6m
777-300ER	$320.2m	$330.0m	$339.6m
777-8		$360.5m	$371.0m
777-9		$388.7m	$400.0m

6.2.6.1 Financing aircraft acquisition

Airlines can finance aircraft purchases from a manufacturer with a fixed or variable interest loan that covers between 70 and 90 per cent of the cost with a mortgage style amortization of up to 12 years (Boeing, 2007; Reuters, 2012). The Commercial Interest Reference Rates (CIRRs) for civil aircraft (in US dollar) is between 1.6 and 3.9 per cent since 2012 for repayment period of less than 15 years (OECD, 2016). The CIRRs are the export credit agencies such as the Export-Import Bank of the United States official lending rates but the actual interest rates paid by each airline will vary depending on the repayment terms (Export-import Bank of the United States, 2016).

In the model, repayments are made yearly and each repayment is:

$$repayment = \frac{principal_0 \times interestRate}{1 - (1 + interestRate)^{-N}} \tag{3}$$

where

$principle_0$ is the initial amount borrowed *interestRate* is the yearly interest rate paid on the loan

N is total number of yearly repayments

The amount still owed after n ($\leq N$) payments is:

$$principal_n = principal_0 \times (1 + interestRate)^n - repayment \times \frac{(1 + interestRate)^n - 1}{interestRate} \quad (4)$$

where

n is the number of repayments made.

Most airlines depreciates the value of their aircraft using a straight-line depreciation method over 15 to 25 years with residue values between zero to 20 per cent (KPMG, 2007). The amount depreciated in each year:

$$yearlyDepreciation = \frac{marketValue_0 - residual\% \times marketValue_0}{depreciationPeriod} \quad (5)$$

The aircraft residual value *i* years after purchase:

$$residualValue_i = marketValue_0 - yearlyDepreciation \times i \quad (6)$$

where

$marketValue_0$ is the market value of the aircraft at the start of the loan

$residualValue_i$ is the residual value after *i* years of depreciation

depreciationPeriod is length of time that the aircraft will be depreciated

residual% is the % of the initial market value remaining at the end of the depreciation period

In 2012, airlines paid from just under one to eight per cent annually (summarised in Table 6.5) on loans on aircraft purchase (AirAsia, 2012; Delta Air Lines, 2012; Hawaiian Airlines, 2012; Virgin Australia, 2012a).

Table 6.5 Airline interest rate paid

Airline	Annual Interest Rates (%)	Maturity period
Delta	0.81 to 6.76	2013-2033
Virgin Australia	0.79 to 6.32	2013-2024
Hawaiian	5.31 to 8	2013-2024
AirAsia X	6.16 to 6.65	2013-2022

The model assumes that airlines puts down 10 per cent initial payment on new aircraft acquisitions, borrow the remaining 90 per cent of the aircraft's (market) value, with repayments made yearly at a fixed interest rate. Airlines will also recoup the full residual value when aircraft is disposed. The aircraft's market value is straight-line depreciated over a period of 25 years with a final residual value of 10 per cent.

This chapter will present results where interest rate is set to two, four, six and eight per cent repaid over 12 and 15 years.

6.2.6.2 Leasing aircraft

A lease gives an airline exclusive use of an aircraft over a period of time for a specified payment. Lease terms will usually include a security deposit, repayment that varies with aircraft supply and demand, age and hours of operation, maintenance reserve that is dependent on hours of operations (Groenenboom et al., 2016). Airlines may also be responsible for the maintenance of their leased aircraft. Leases repayments can be made monthly, quarterly, annually or some other basis over the lease period. The repayment amount can be fixed or variable during the lease period with most leases in US dollars (Groenenboom et al., 2016). The lease period for newer aircraft can range from five to 10 years whereas the lease period for older aircraft is between four to five years. Lease rate factor (LRF) is the lease rate divide by the aircraft value and can range from 9.6 to 18 per cent per annum. Older aircraft are usually on higher LRF but shorter terms whereas newer aircraft are on lower LRF but longer terms (Timotijevic, 2013). By comparing the market value of each aircraft type to the list price, Schonland (2016) determined that each aircraft type were subject to at least 45 per cent discount. According to Ascend (2013, 2014a, 2014b, 2015) discount on new aircraft can be as high as 60 per cent with LRF of between nine and 12 per cent (Table 6.6).

Table 6.6 List price, market value and lease rates

Aircraft	Year	List price (Million$)	Market value for newest (Million$)	Market value / List price (%)	Discount (%)	Lease rate per annum for newest (Million$)	LRF=lease rate /market value (%)
A320	2013	91.5m	40.5m	44.26	55.74	3.84m	9.48
	2014	93.9m	43m	45.79	54.21	4.32m	10.05
	2015	97m	44m	45.36	54.64	4.68m	10.64
A330-200	2013	216.1m	87m	40.26	59.74	10.2m	11.72
	2014	221.7m	93.5m	42.17	57.83	10.32m	11.04
	2015	229m	93.5m	40.83	59.17	9.84m	10.52
A330-300	2013	239.4m	91m	38.01	61.99	10.8m	11.87
	2014	245.6m	104m	42.34	57.66	10.92m	10.5
	2015	253.7m	105.m	41.39	58.61	11.04m	10.51
737-800	2013	90.5m	46m	50.83	49.17	4.32m	9.39
	2014	93.3	48m	51.45	49.55	4.8m	10
	2015	96m	48.3m	50.3	49.7	4.92m	10.19
777-300ER	2013	320.2m	162m	50.59	49.41	18.6m	11.48
	2014	330m	166m	50.3	49.7	19.2m	11.57
	2015	339.6m	167m	49.17	50.83	18.6m	11.14
787-8	2014	218.3m	115.5m	52.9	47.1	13.2m	11.43
	2015	224.6m	120m	53.43	46.57	13.2m	11

In the model, the LRF is 10 per cent of the market value. The market value of a new aircraft is set at the discounted list price which is straight line depreciated over 25 years with a final 10% residual value. For current generation of aircraft such as 737NGs, A320s, A330s and 777-300ERs the list price is discounted by 50 per cent but for the next generation of aircraft such as 737MAXs, A320NEOs, 787s and 777Xs, the list price is discounted by 40 per cent (Reuters, 2012). The lease period is five years with lease rates recalculated at the end of the lease and airlines are responsible for the maintenance. Other lease costs such as a security deposit and maintenance reserve are not included in the simulation.

6.2.7 Maintenance cost of aircraft

According to International Air Transport Association (IATA), flying newer more fuel efficient aircraft lowers maintenance costs (M. Smyth & Pearce, 2006). The total maintenance costs of US airlines which include airframes, engines and overhead costs, increased at a rate of 17.6 per cent per annum during the first six years of a new aircraft and 3.5 per cent annually for aircraft between six and 12 years old (Dixon, 2006). The large increase in maintenance cost in the first six years was due to aircraft coming out of the new aircraft warranty and the airlines having to pay for all subsequent maintenance. For aircraft older than 12 years (i.e. after 2nd D-check) their results show a 0.7 per cent per annum growth i.e. as the aircraft ages, maintenance cost does not increase rapidly (Dixon, 2006). The age of the aircraft in their study were up to 25 years with US airlines disposing their aircraft at around 25 years. This closely matches the findings in the white paper published by Forsberg (2015) which states that the average retirement age of all commercial jets are around 25.7 years.

Maintenance cost of 787s are expected to be 15 per cent lower than 767s but aircraft such as the 737MAXs, A320NEOs and 777Xs are expected to have maintenance cost similar to the superseded 737NGs, A320s and 777-200LR/300ERs respectively (Forsberg & Mollan, 2013; Gubisch, 2013; Qiu, 2005). According to IATA, the average maintenance cost of 2,834 aircraft flown by 23 airlines in 2012 was US$3.26 million per aircraft (Markou & Cros, 2013). Table 6.7 summarises the annual maintenance cost for each aircraft type in 2012 (dollars).

In the model, maintenance costs, which are in 2012 dollars, are adjusted for inflation over the simulation period of 2013 to 2033.

Table 6.7 Maintenance cost in 2012

Aircraft	Aircraft numbers	Average age (years)	Maintenance cost (Billion$)	Maintenance cost per Aircraft (Million$)
A320 Family	596	7.3	$1.51bn	$2.5m=1.51bn/596
A330	171	5.9	$0.78bn	$4.6m=0.78bn/171
777	240	7.8	$1.49bn	$6.2m=1.49bn/240
737NG	510	6.8	$0.86bn	$1.7m=0.86bn/510
747-400	129	15.4	$0.89bn	$6.9m=0.89bn/129
767	233	17.6	$0.86bn	$3.7m=0.86bn/233

6.2.8 Fuel cost

In 2015, fuel represented 27 per cent of airline operating costs and has stayed at approximately 30 per cent since 2006 (International Air Transport Association (IATA), 2016). Table 6.8 summarises the cost of jet fuel from 2013 to 2015 and the predicted cost of jet fuel in 2013 dollars for the next 20 years (U.S. Energy Information Administration, 2015a, 2015b). Each tonne of fuel is approximately 328 US gallons.

In the model, costs of fuel which are in 2013 dollars are adjusted for inflation over the simulation period of 2013 to 2033.

Table 6.8 Jet fuel cost

Year	2013	2014	2015	2020	2025	2030	2035
Fuel cost in 2013 US$/US gal	$2.92	$2.69	$1.52	$2.17	$2.47	$2.88	$3.31

6.2.9 Inflation rate

The US inflation rate is forecasted to be between two and 2.5 per cent up to 2060 (Knoema, 2015; U.S. Department of Labor, 2015).

In the model, inflation is assumed to be increasing at a constant yearly rate of 2.25 per cent over the simulation period of 2013 to 2033.

6.3 Scenarios definition

6.3.1 Modify/improve current fleet

In *Scenarios 2 to 4* of Yin et al. (2016) the growth in emissions from 2013 to 2033 was simulated as a combination of emissions from airlines servicing routes from 2012 and from new aircraft acquired to service the passenger and cargo growth.

Three strategies for modifying and improving the 2012 fleet were presented in Yin et al. (2016). Eight abatement options in *Strategy 1* were applied to as many aircraft in 2012 fleet as possible, which resulted in just over three per cent emissions reduction by 2033. In *Strategy 3,* the current fleet of 737NGs, A320s, A330s, 767s, 747-400s, 777-200LRs and 777-300ERs were renewed, which resulted in over 15 per cent CO_2 reduction by 2033. *Strategy 2* combines *Strategy 1* with renewing the current fleet of 747-400s with 777-300ERs and 787-9s and resulted in more than seven per cent reduction in CO_2 emissions by 2033.

In the model, the reference scenario will renew the 2012 fleet of 737NGs with 737MAXs, A320s with A320NEOs, A330s/767s with 787-8s, 777-200LR/300ERs with 777Xs, Qantas 747s with 787-9s and non-Australian 747s with 777-300ERs when the current aircraft are 25 years old (Table 6.9).

The cost of additional CO_2 reduction for each abatement option (from *Strategy 1* and aircraft renewal *Strategy 3)* will be compared to this reference scenario. The year these abatement options are implemented are also specified in *Strategy 1* and *Strategy 3* and are summarised in Table 6.9. MACCs for each Australian airline and for the entire non-Australian-based international fleet are produced.

Table 6.9 Modify/improve current fleet

Reference Scenario	Abatement options
Renew 737NG @ 25 years old with 737MAX. Renew A320 @ 25 years old with A320NEO. Renew A330/767 @ 25 years old with 787-8. Renew 777-200LR/300ER @ 25 years old with 777X. Renew Qantas 747 @ 25 years old with 787-9. Renew non Australian 747 @ 25 years old with 777-300ER	Renew 737NG with 737MAX in 2018.
	RenewA320 with A320NEO in 2018.
	Renew A330/767 with 787-8 in 2014.
	Renew 777-200LR/300ER with 777X in 2021.
	Renew Qantas 747 with 787-9 in 2017.
	Renew non Australian 747 747 to 777-300ER in 2014.
	Wash Engines three times every year.
	Reduce Number of Engines used during Taxi.
	Install &renew Lightweight Seats every 7 years.
	Install and renew iPad Electronic Flight Bag every 3 year.
	Install &renew Lightweight IFE every 7 years.
	Install 737NG scimitar winglets in 2013.
	Install 767-300 winglets in 2013.
	Install A320 Sharklets in 2014.

6.3.1.1 Aircraft number and age of current fleet

The cost of each abatement option (in Table 6.9) will depend on the number of aircraft affected, type and age of aircraft, distance flown, and the year the abatement option was implemented. Since the study ends in 2033, the full abatement potential might only be realised beyond the end of the study period. The total number of aircraft, number of seats, number of 737NGs, A320s, 767s, A330s, 777-200LR/300ERs and 747s can be estimated from the 2012 flight schedule and airline's annual reports.

IATA published the daily utilisation of each aircraft family for 23 airlines. The flight hours per flight are short when compared to the length and flight times of Australian international flights. According to IATA, 777 flights are on average 5.3 hours long with daily utilization of 11.1 hours. This equates to just over two flights per day. The flight times for A320s and 737s are also shorter at 1.9 and 2.3 hours respectively with daily utilization at 8.5 hours. This equates to just over four flights per day. The daily utilization for long and medium haul aircraft are all in excesses of 10 hours and only 8.5 hours for short haul and this can be attributed to the multiple take offs, landings and turnarounds per day. (Markou & Cros, 2013).

Virgin Australia, Emirates and Etihad fly 777s in excess of 12 hours on their long haul Australian international flights. Since long haul flights are over 12 hours long, in the model airlines can only operate one long haul flight per day. A320s and 737s on Australian international flights are at least three hours long and are mainly flown between Australia and New Zealand. For example a Qantas 737-800 flying between Brisbane and Auckland can perform two inbound and two outbound flights in one day. Depending on the length of the medium haul route, a 767 or A330 can perform one medium haul flight to Honolulu but can fly from Australia to Southeast Asia and back in one day. In 2012, average short, medium and long haul Australian international flights are approximately 2,944km, 6,847km and 12,210km long and the model assumes that aircraft flown on short, medium and long haul routes can perform four, two and one flight per day respectively.

Non-Australia-based airlines deploy only a fraction of their entire fleet for flights to and from Australia. In this thesis, MACCs are not produced for each individual non-Australia-based airline flying to and from Australia but grouped together. In 2012, the types and numbers of aircraft deployed and their average age are presented in Table 6.10 (Airfleets, 2016). The average age of A340s, A380s and 777-200/200ER/300s were not included in Table 6.10 since they will not be replaced by newer aircraft in this study.

Table 6.10 Non-Australia-based fleet numbers and age in 2012

Non-Australia-based Airlines	A320/321	A330-200/300	A340	A380	737NG	747-400	767-300	777-200/200ER/300	777-200LR/300ER	Total
Total number of aircraft (round)	7	25	5	6	1	5	2	5	12	68
Average age in years	6	7			5	15	16		3	

For Australia-based airlines, additional information from their annual reports is used to determine the number of aircraft in their international fleet. Qantas has a fleet of A380s and 747s, which are mainly used on their long and medium haul international flights. Qantas utilises 20 767s, 10 A330-200s, 10 A330-300s and 66 737s on both medium and short haul international and domestic routes. Jetstar flies A330-200s on their medium haul international flights to Japan, Hawaii and Indonesia and almost 100 A320s and A321s on both domestic and international short haul routes (Qantas, 2013a). Virgin Australia flies only 777-300ERs on long haul international routes to USA and UAE and 737s on both domestic and international short haul to New Zealand and Indonesia (Virgin Australia, 2013a).

Focusing on the 2012, international flights analysed in Yin et al. (2015), only a subset of Qantas 737s, 767s and A330s, Jetstar A320s and Virgin 737s are included in this study. Table 6.11 shows the number of aircraft for each Australia-based airline and the average age of A320s, A321s, A330s, 737s, 747s, and 777s (Airfleets, 2016). The average age of Qantas A380 was not included in Table 6.11 since they will not be replaced by newer aircraft in this study.

Table 6.11 Australia-based airline fleet numbers & age in 2012

Australia-based Airlines		A320	A321	A330-200	A330-300	A380	737NG	747-400	747-400ER	767-300	777-300ER	Total
Qantas	Number of aircraft			3	6	12	8	10	6	2		47
	Average Age in years			3	8		2	19	9	19		
Virgin Australia	Number of aircraft						11				5	16
	Average Age in years						6				3	
Jetstar	Number of aircraft	9	2	10								21
	Average Age in years	4	6	5								

6.3.2 Aircraft acquisition for growth

Two aircraft acquisition strategies to handle the growth in passenger and freight traffic were also presented in Yin et al. (2016). In the first, 777-300ERs, A330s and even numbers of 737NGs and A320s were acquired to service the growth in long, medium and short haul passengers and cargo. These aircraft were also modified with additional emissions abatements equipment (such as lightweight seats, IFEs). In the second more aggressive acquisition strategy, 777-300ERs, A330s, 737NGs and A320s were acquired before switching to 777Xs, 787s, 737MAXs and A320NEOs for long, medium and short haul growth.

In the model, the reference aircraft acquisition scenario is similar to the first aircraft acquisition strategy (in Yin et al. (2016)) where 777-300ERs, A330s, 737NGs and A320s were acquired to service long, medium and short haul traffic growth from 2013 to 2033. This reference scenario assumes that airlines will purchase 777-300ERs till 2021, A330s, 737NGs and A320s till 2018 before switching to leases since these aircraft will be out of production (Table 6.12). The year of manufacture for all leased 777-300ERs are 2020, A330s, A320s and 737NGs are 2017.

The cost of additional CO_2 reduction for each abatement options (in Table 6.12) such as acquiring new aircraft, reducing number of engines used in taxiing, performing engine washes, installing iPad EFBs, upgrading to light weight seats and IFEs will be compared against this reference aircraft acquisition scenario.

Table 6.12 Aircraft acquisition for growth

Reference aircraft acquisition scenario	Abatement options
Acquire 737NG and A320 for Short haul routes (Finance till 2017, lease from 2018). Acquire A330 for Medium Haul routes (Finance till 2017 and lease from 2018). Acquire 777-300ER for Long haul routes (Finance till 2020 and lease from 2021)	Acquire 737NG and A320 for Short haul routes till 2017, then 737MAX and A320NEO from 2018.
	Acquire A330 for Medium Haul routes till 2013 then 787-8 from 2014.
	Acquire 777-300ER for Long haul routes till 2020 then 777X from 2021.
	Wash Engines three times every year.
	Reduce Number of Engines used during Taxi.
	Install &renew Lightweight Seats every 7 years.
	Install and renew iPad Electronic Flight Bag every 3 year.
	Install &renew Lightweight IFE every 7 years.

6.3.2.1 Number of additional aircraft

The most popular aircraft used in 2012 were the 777-300ERs for long haul flights, A330s for medium haul flights and a combination of A320s and 737NGs for short haul flights (Yin et al., 2015). These long, medium and short haul flights had approximately 309, 260 and 163 passengers on each flight respectively (Yin et al., 2015). Figure 6.1 show the number of additional short, medium and long haul aircraft required to service the growth in passenger and freight.

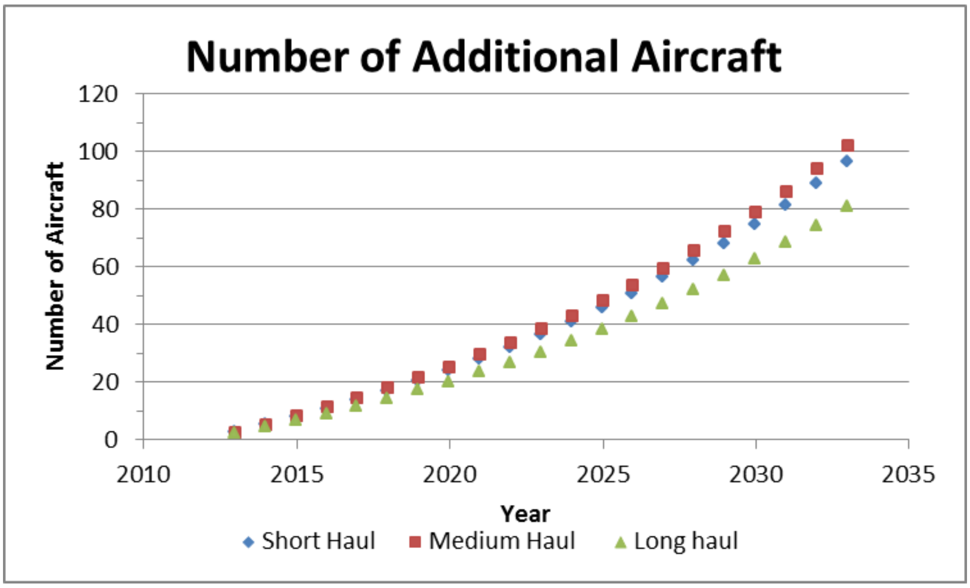

Figure 6.1 Number of additional aircraft to service traffic growth

6.4 Results and Discussions

6.4.1 Modify and/or improve 2012 fleet

The reference scenario (Table 6.9) used in the model assumes that airlines will renew their 2012 fleet of aircraft when they are 25 years old. The MACCs (Figure 6.2, Figure 6.3, Figure 6.4 and Figure 6.5) for Virgin Australia, Jetstar, Qantas, and non-Australian fleet shows marginal cost and CO_2 abatement potential of these abatement options (Table 6.9) relative to this reference scenario between 2013 and 2033. The MACCs indicate that the cost of fuel saved by reducing number of engines used during taxiing, washing aircraft engines three times a year and installing iPad based EFB more than outweigh the cost of implementing these abatement options for all airlines. Whereas the cost of fuel saved by installing lightweight IFEs over the next 20 years cannot justify the high cost of installing and refurbishing every seven years for any airlines. Airlines install IFEs for many reasons other than just reducing fuel used and since some seats are closely integrated with IFEs there might be some cost advantages in installing them together that have not being modelled (D. Owen, 2014).

Whether winglets are retrofitted on 767s, 737s and A320s will depend on the age of the aircraft, number of flights and if the cost of installation can be recouped before the aircraft's retirement. Qantas 767s are on average 19 years old and are used on a limited number of international flights. The cost of fuel saved from installing winglets on these 767s prior to retirement in six years' time will not offset the cost of installation. On the other hand, 767s flown by non-Australian airlines are on average 16 years old and the cost of installing winglets will be recouped from the cost of fuel saved over the nine years prior to aircraft's retirement. Virgin Australia 737NGs, Qantas 737NGs and Jetstar A320s are between two and six years old in 2012 and the cost of retrofitting all with 737 scimitar winglets and A320 Sharklets will be recouped and this is also true of non-Australia-based A320s used mainly by Air New Zealand but not so for the small number of older non-Australian 737NGs.

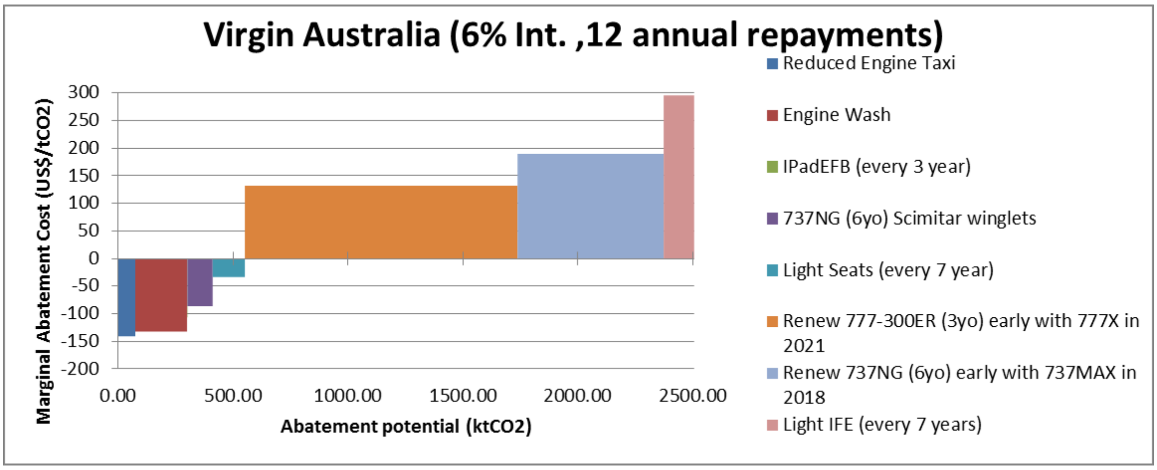

Figure 6.2 MACC for Virgin Australia (2013-2033)

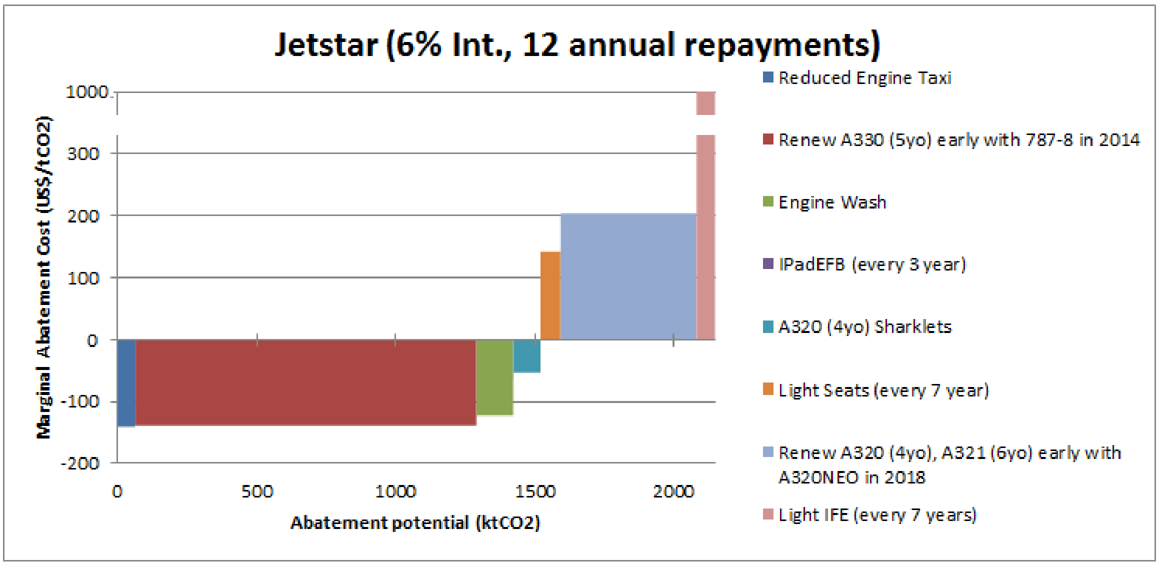

Figure 6.3 MACC for Jetstar (2013-2033)

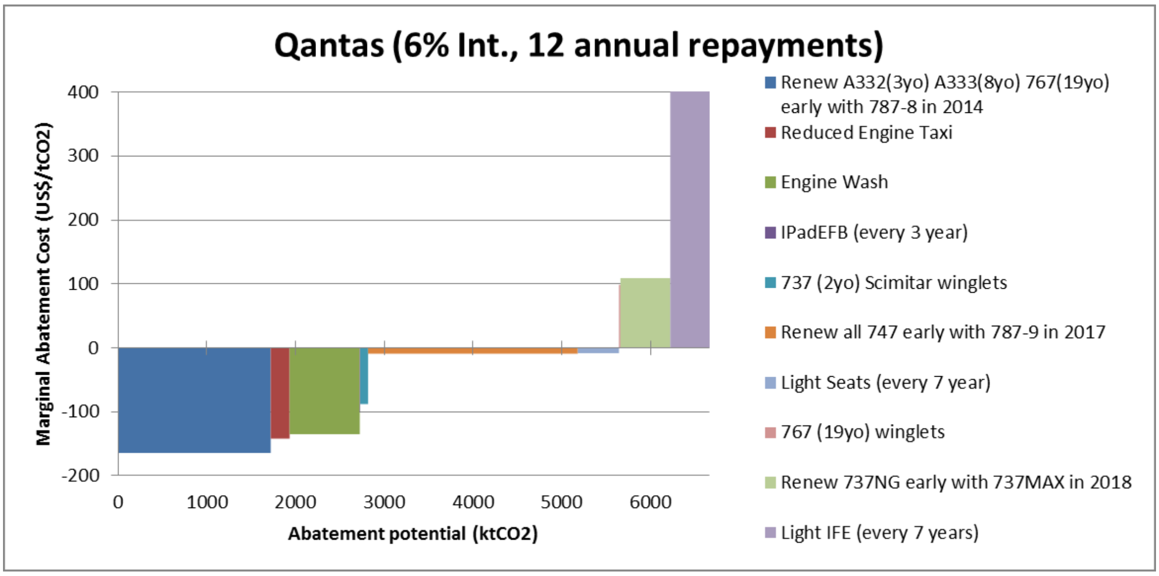

Figure 6.4 MACC for Qantas (2013-2033)

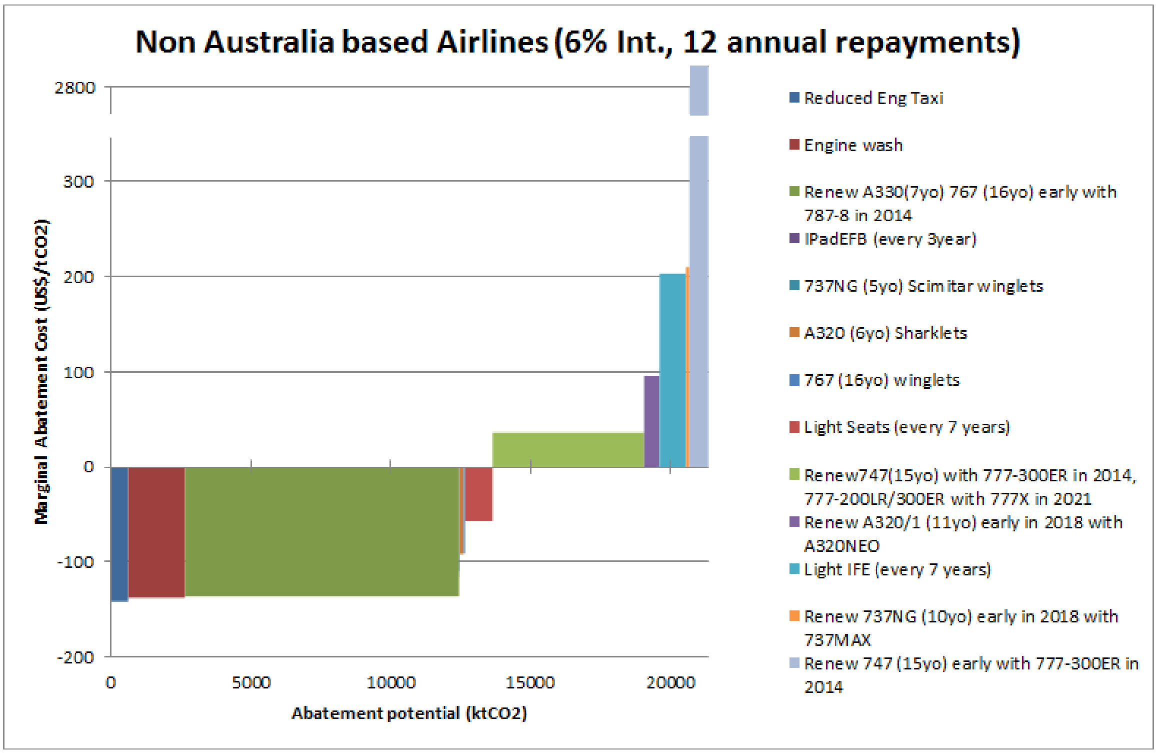

Figure 6.5 MACC for Non-Australia-airlines (2013-2033)

Renewing the fleet with newer more fuel efficient aircraft will reap the most CO_2 emissions reduction (Table 6.13, Table 6.16 and Table 6.19). The model assumed that airlines would finance the purchase of the new aircraft and airlines will pay up to eight per cent per annum in interest, which is up to four per cent higher than the Organisation for Economic Cooperation and Development (OECD) CIRR for aviation. Table 6.14, Table 6.15, Table 6.17, Table 6.18, Table 6.20 and Table 6.21 show the change in cost of abating one tonne of CO_2 as interest rates and repayment terms are varied. Airlines will have to weigh the cost of acquiring the new aircraft, residual value and amount still owing on the superseded aircraft against fuel cost saved and reduction in maintenance cost. The results show that there is no financial advantage for Virgin

Australia to replace their young international fleet of 737NGs and 777-300ERs (Table 6.14 and Table 6.15), whereas Qantas should renew 747-400s in 2017 (Table 6.20 and Table 6.21). Jetstar's fleet of A330-200s and Qantas's mixed fleet of A330-200s, A330-300s and older 767s should be replaced by 787-8s in 2014. As expected, marginal abatement cost for each option decreased as interest rates are decreased (Table 6.17, Table 6.18, Table 6.20 and Table 6.21). As the repayment period is increased from 12 years to 15 years, the expectation is that these abatement options will be cheaper. However, this is not always the case; for example by increasing the repayment term to 15 years the NPV of acquiring 787-9 to replace Qantas 747s increased when compared to a repayment term of 12 years (Table 6.20 and Table 6.21). This is because most of the Qantas 747s are more than 15 years old and assumed to be paid for.

Table 6.13 Virgin Australia – CO_2 Saved

	Renew 777-300ER with 777X	Renew 737NG with 737MAX
CO_2 saved(kt)	1,186.7	636.6

Table 6.14 Virgin Australia – Marginal Abatement Cost (US$/t$CO_2$) 12 annual repayments

Interest rate	Renew 777-300ER with 777X	Renew 737NG with 737MAX
2%	$34.98	$63.88
4%	$82.02	$125.02
6%	$131.86	$189.79
8%	$184.33	$257.98

Table 6.15 Virgin Australia – Marginal Abatement Cost (US$/t$CO_2$) 15 annual repayments

Interest rate	Renew 777-300ER with 777X	Renew 737NG with 737MAX
2%	-$21.73	$49.91
4%	$23.16	$117.45
6%	$70.78	$189.21
8%	$120.87	$264.80

Table 6.16 Jetstar – CO_2 Saved

	Renew A330 with 787-8	Renew A320 with A320NEO
CO_2 saved(kt)	1,224.8	489.4

Table 6.17 Jetstar – Marginal Abatement Cost (US$/t$CO_2$) 12 annual repayments

Interest rate	Renew A330 with 787-8	Renew A320 with A320NEO
2%	-$260.27	$43.42
4%	-$200.80	$121.51
6%	-$139.37	$203.78
8%	-$76.18	$289.93

Table 6.18 Jetstar - Marginal Abatement Cost (US$/t$CO_2$) 15 annual repayments

Interest rate	**Renew A330 with 787-8**	**Renew A320 with A320NEO**
2%	-$264.26	$27.28
4%	-$203.24	$111.20
6%	-$140.39	$199.67
8%	-$76.02	$292.19

Table 6.19 Qantas – CO_2 Saved

	Renew 747 with 787-9	**Renew A330, 767 with 787-8**	**Renew 737NG with 737MAX**
CO_2 saved(kt)	2,361.1	1,721.4	561.4

Table 6.20 Qantas – Marginal Abatement Cost (US$/t$CO_2$) 12 annual repayments

Interest rate	**Renew 747 with 787-9**	**Renew A330, 767 with 787-8**	**Renew 737NG with 737MAX**
2%	-$74.05	-$240.22	$12.51
4%	-$42.52	-$203.10	$59.73
6%	-$9.07	-$164.46	$108.53
8%	$26.20	-$124.43	$160.10

Table 6.21 Qantas– Marginal Abatement Cost (US$/t$CO_2$) 15 annual repayments

Interest rate	**Renew 747 with 787-9**	**Renew A330, 767 with 787-8**	**Renew 737NG with 737MAX**
2%	-$64.17	-$235.69	$4.93
4%	-$24.85	-$196.33	$54.72
6%	$17.25	-$155.50	$106.67
8%	$61.94	-$113.42	$160.51

Table 6.22 shows the amount of CO_2 saved for renewing some of the non-Australian airlines' fleet that served Australian routes in 2012. The cost of upgrading non-Australian 747s that are on average 15 years old to more efficient 777-300ERs cannot be recouped due to limited number of flights flown by these 747s. The marginal abatement cost did not improve by decreasing interest rates and increasing the repayment terms since 747s were paid for (Table 6.23 and Table 6.24). On the other hand replacing 747s with 777-300ERs and then all 777-200LR/300ERs with 777Xs in 2021 appears to be the better economic option if the changeover costs can be kept low through low interest rate finance, longer repayment term and discounts on aircraft list price.

Table 6.22 Non-Australian airlines – CO_2 Saved

	Renew 747 with 777-300ER	Renew 747 with 777-300ER and all 777-200LR/ 300ER with 777X	Renew A330, 767 with 787-8	Renew A320 with A320NEO	Renew 737NG with 737MAX
CO_2 Saved (kt)	687.0	5,411.4	9,799.9	558.5	121.4

Table 6.23 Non-Australian airlines – Marginal Abatement Cost (US$/t$CO_2$) 12 annual repayments

Interest rate	Renew 747 with 777-300ER	Renew 747 with 777-300ER and all 777-200LR/ 300ER with 777X	Renew A330, 767 with 787-8	Renew A320 with A320NEO	Renew 737NG with 737MAX
2%	$2481.65	-$36.79	-$175.74	$7.86	$147.00
4%	$2670.19	-$1.27	-$156.31	$50.66	$177.65
6%	$2870.24	$36.17	-$136.03	$95.99	$210.03
8%	$3081.19	$75.41	-$114.97	$143.71	$244.04

Table 6.24 Non-Australian airlines – Marginal Abatement Cost (US$/t$CO_2$) 15 annual repayments

Interest rate	Renew 747 with 777-300ER	Renew 747 with 777-300ER and all 777-200LR/ 300ER with 777X	Renew A330, 767 with 787-8	Renew A320 with A320NEO	Renew 737NG with 737MAX
2%	$2527.01	-$70.59	-$174.02	-$1.50	$139.11
4%	$2765.50	-$35.77	-$153.36	$45.66	$172.35
6%	$3021.82	$0.99	-$131.87	$95.74	$207.54
8%	$3294.78	$39.50	-$109.66	$148.47	$244.49

6.4.2 Acquiring new aircraft to handle Passenger and Cargo growth

Figure 6.6 shows the additional cost and CO_2 reduction potential of each additional abatement option (in Table 6.12) relative to the reference aircraft acquisition scenario (in Table 6.12). It shows that the lightweight IFEs are not a financially viable option due to the high cost whereas reduced engine taxiing, engine washing, iPad EFBs and light weight seats should be considered. In the “aggressive” aircraft acquisition strategy, airlines acquire the most popular aircraft currently flown before switching to the next generation of long, medium and short haul aircraft. Table 6.25 shows the amount of CO_2 saved when applying this “aggressive” aircraft acquisition strategy. This strategy becomes more financially viable as interest rates decreased or repayment periods increased from 12 years (Table 6.26) to 15 years (Table 6.27) on the assumption that airlines are receiving discounts of 40 to 50 per cent on aircraft list price and financing 90 per cent of the purchase. Since the analysis ends in 2033 and A320NEOs/737MAXs are acquired in 2018 and 777Xs in 2021, the full abatement potential of these aircraft are not realised hence the higher cost for each ton of CO_2 abated when compared to 787s which are acquired in 2014.

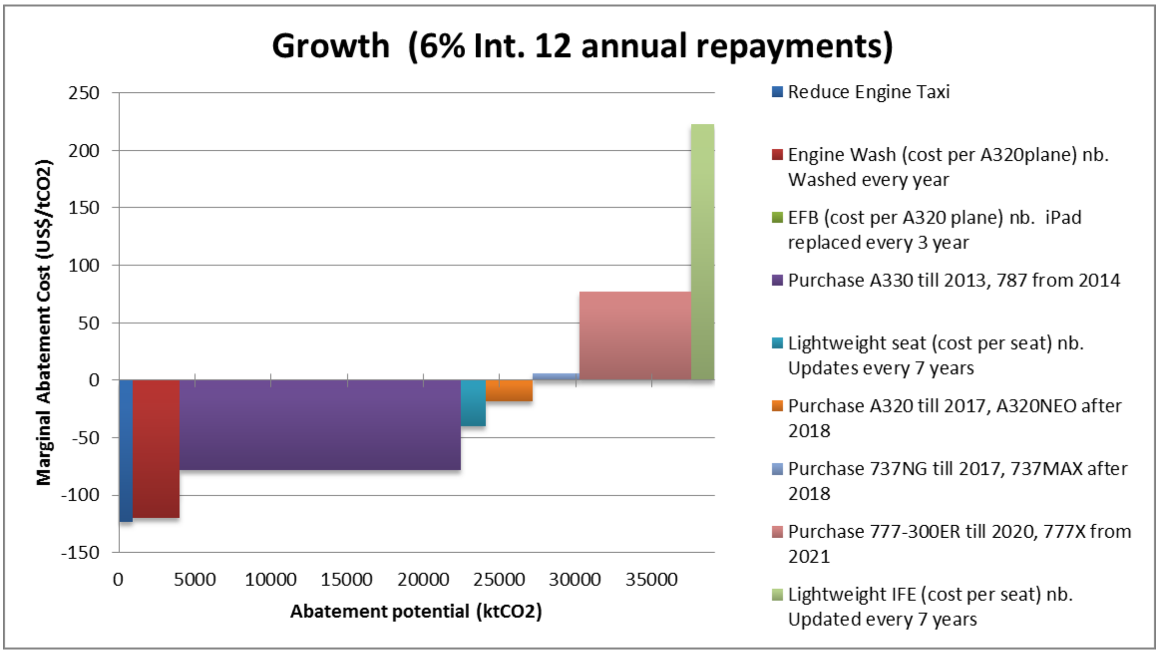

Figure 6.6 MACC for Additional aircraft for Traffic Growth (2013-2033)

Table 6.25 Acquire additional aircraft for Traffic growth - CO_2 Saved

	Acquire 777-300ER & 777X	Acquire A330 & 787	Acquire 737NG & 737MAX	Acquire A320 & A320NEO
CO_2 saved(kt)	7,305.3	18,463.6	3,094.1	3,081.4

Table 6.26 Acquire additional aircraft for Traffic growth - Marginal Abatement Cost (US\$/tCO_2) 12 annual repayments

Interest rate	Acquire 777-300ER & 777X	Acquire A330 & 787	Acquire 737NG & 737MAX	Acquire A320 & A320NEO
2%	-$2.26	-$113.19	-$39.94	-$62.30
4%	$36.28	-$96.27	-$17.78	-$40.83
6%	$77.18	-$78.32	$5.73	-$18.04
8%	$120.30	-$59.39	$30.52	$5.99

Table 6.27 Acquire additional aircraft for Traffic growth - Marginal Abatement Cost (US$/t$CO_2$) 15 annual repayments

Interest rate	**Acquire 777-300ER & 777X**	**Acquire A330 & 787**	**Acquire 737NG & 737MAX**	**Acquire A320 & A320NEO**
2%	-$56.05	-$133.35	-$67.14	-$88.68
4%	-$17.11	-$115.72	-$44.19	-$66.42
6%	$24.75	-$96.77	-$19.51	-$42.50
8%	$69.31	-$76.60	$6.77	-$17.03

If airlines implemented all the financially viable abatement options where purchased aircraft are financed on six per cent interest repaid over 12 years then CO_2 emissions would be 33.6Mt by 2033 (Supplemental data Table 6.31) with emissions increasing at an average rate of 4.8 per cent annually from 2013 to 2033. By decreasing interest rate to two per cent, acquiring the latest 777X and 737 MAX (Table 6.26 and Table 6.27) to transport the growth in long and short haul passenger traffic became financially viable and emissions drop to 31.7Mt of CO_2 in 2033 (Supplemental data Table 6.31) with emissions increasing at 4.5 per cent annually. This is lower than the 32.1Mt in Yin et al. (2016) which was achieved by only acquiring new fuel efficient aircraft to renew the current fleet and service the passenger and cargo growth. The slight decrease was achieved by also implementing other complimentary abatement options such as performing additional engine washing, reducing engine used during taxiing, installing iPad EFBs and light weight seats.

The emission drop due to a drop in interest rate to 2 per cent was not uniformly distributed to all airlines. Jetstar saw only a 2 per cent drop in emissions in 2033 since it does not fly long haul and the model assumes all growth in short haul flights will be evenly split between A320s and 737s whereas Virgin and Qantas saw a drop of, 6.4 per cent and 4.6 per cent in CO_2 emission respectively (Supplemental data Table 6.28, Table 6.29 and Table 6.30). In 2012, both Qantas and Virgin Australia were operating at a CO_2 efficiency of 0.73g/kg-km while the average for all airlines was 0.71g/kg-km. By 2033 Qantas had improved its efficiency to match the average in 2033 but Virgin Australia did not (Supplemental data Table 6.28, Table 6.29 and Table 6.30). Virgin Australia has very few long haul flights and acquiring 777X in 2021 will improve its CO_2 profile but there is not enough flight to make its CO_2 efficiency match the average by 2033.

6.5 Conclusions

Airlines can reduce CO_2 emissions by retrofitting their current fleet with CO_2 reducing technologies, by changing their operations, renewing their current fleet and by acquiring more fuel efficient aircraft. One of the many factors that will determine if an airline implements certain emission abatement options will be cost of acquisition, installation, maintenance and fuel over the remaining useful life of each aircraft. Due to the high cost of new aircraft, most airlines will either lease or finance the cost of their purchase with the payment terms and interest rates dependent on each airline's specific circumstances. Marginal abatement cost is the additional cost of each abatement option relative to a reference scenario. In the model, the reference scenario assumes that airlines will keep an aircraft in its fleet for 25 years before renewing. MACCs are used to graphically indicate the potential impact of each CO_2 emission abatement option with each option ranked according to the amount spent/saved per tonne of CO_2 saved.

CO_2 emissions from 2013 to 2033 were studied as a combination of emissions from airlines flying the 2012 schedule and also from a fleet of new aircraft acquired to transport the six per cent and five per cent growth in passengers and cargo respectively. MACCs were produced for all three Australia-based airlines and non-Australia-based aircraft flying into and out of Australia. A MACC was also produced for the fleet of new long, medium and short haul aircraft that will service the traffic growth.

The MACCs show that installing lightweight IFEs are not a financially viable emissions abatement option whereas lightweight seats are (except for Jetstar). Seats and IFEs are tightly integrated together and are seen by airlines as a means to differentiate their product from their competitor and emission reduction might not be the only requirement in deciding if they are installed. Reducing the number of engines used during taxiing, washing the engines three times every year and installing iPad (tablet) based EFBs are emissions and financially saving options for both the current fleet and the fleet of new aircraft even after outlaying the implementation cost. Whether to retrofit winglets to 767s, A320s and 737NGs will depend on the aircraft age and the amount of flying that airline will do with these modified aircraft. For Australia-based airlines, cost of retrofitting 737s and A320s with winglets will be recouped but due to the age of Qantas 767s and the limited number of international flights flown installing 767 winglets is not a financially viable emission reduction option. On the other hand non-Australian 767s are generally younger and the cost of winglets will be recouped.

Even though renewing the current fleet and acquiring the latest aircraft to service growth will produce the highest CO_2 emissions reduction, it was not always the most cost effective option especially if the superseded aircraft are relatively new or they are flown only on a few flights. For example 747-400s are flown by Qantas and non-Australia airlines on Australian international routes with Qantas using them extensively on long haul routes. The MACCs shows it makes more economic sense for Qantas to replace 747s in 2017 with 787-9s but not for non-Australia 747s, which account for low number of flights. Low interest financing and longer repayment period will increase the likelihood of airlines acquiring the latest aircraft to service traffic growth but has a lower impact on airlines renewing the current fleet. The decision to renew the current fleet will dependent on not only the cost of acquiring the new aircraft but also the cost of disposing the superseded aircraft (i.e. residual and amount still owed), the savings in fuel and maintenance and the amount of flying done on these aircraft.

This chapter focused on how costs influence how airlines are likely to implement certain emission abatement options. Australia-based airlines sometimes use the same aircraft on both international and domestic routes and a more specially derived MACC for those circumstances would need to include all aircraft and flights. Since non-Australia-based airlines flies only a fraction of their fleet to service Australian international flights, the MACC did not differentiate between airlines that are emissions efficient. Additional research should be undertaken to determine other cost incentives and penalties that would induce all airlines flying into and out of Australia to take on additional abatement options. Some of these incentives and penalties may include pricing CO_2 emissions, tax incentives, subsidizing abatement options and penalizing poor CO_2 efficiency and low load factors.

6.6 Supplementary data

Table 6.28 Jetstar CO_2 emissions profile

	6% per annum 12 year		2% per annum 12 year	
Year	Tot CO_2 (t)	g/kg-km	Tot CO_2 (t)	g/kg-km
2012	530,579.78	0.71	530,579.78	0.71
2013	543,110.88	0.69	543,110.88	0.69
2014	494,916.47	0.60	494,916.47	0.60
2015	517,300.66	0.59	517,300.66	0.59
2016	541,027.89	0.59	541,027.89	0.59
2017	566,178.76	0.58	566,178.76	0.58
2018	591,879.53	0.57	590,914.40	0.57
2019	619,122.35	0.57	617,134.18	0.56
2020	647,999.75	0.56	644,927.15	0.55
2021	678,609.78	0.56	674,387.70	0.55
2022	711,056.42	0.55	705,615.88	0.54
2023	745,449.85	0.55	738,717.75	0.54
2024	781,906.89	0.55	773,805.73	0.53
2025	820,551.35	0.54	810,998.99	0.53
2026	861,514.48	0.54	850,423.85	0.53
2027	904,935.40	0.54	892,214.20	0.52
2028	950,961.58	0.53	936,511.96	0.52
2029	999,749.32	0.53	983,467.60	0.51
2030	1,051,464.33	0.53	1,033,240.57	0.51
2031	1,106,282.24	0.52	1,085,999.92	0.51
2032	1,164,389.22	0.52	1,141,924.84	0.51
2033	1,225,982.62	0.52	1,201,205.25	0.50

Table 6.29 Virgin Australia CO_2 emissions profile

	6% per annum 12 year		2% per annum 12 year	
Year	Tot CO_2 (t)	g/kg-km	Tot CO_2 (t)	g/kg-km
2012	898,027.53	0.73	898,027.53	0.73
2013	918,889.76	0.71	918,889.76	0.71
2014	956,970.11	0.69	956,970.11	0.69
2015	1,003,809.51	0.69	1,003,809.51	0.69
2016	1,053,459.27	0.68	1,053,459.27	0.68
2017	1,106,088.01	0.67	1,106,088.01	0.67
2018	1,160,891.79	0.66	1,159,902.97	0.65
2019	1,218,983.80	0.65	1,216,946.82	0.65
2020	1,280,561.32	0.65	1,277,413.31	0.64
2021	1,345,833.50	0.64	1,334,341.13	0.63
2022	1,415,022.01	0.63	1,394,684.62	0.62
2023	1,488,361.83	0.63	1,458,648.72	0.61
2024	1,566,102.04	0.62	1,526,450.67	0.60
2025	1,648,506.66	0.62	1,598,320.73	0.60
2026	1,735,855.56	0.61	1,674,503.00	0.59
2027	1,828,445.39	0.60	1,755,256.20	0.58
2028	1,926,590.62	0.60	1,840,854.60	0.58
2029	2,030,624.55	0.59	1,931,588.90	0.57
2030	2,140,900.52	0.59	2,027,767.26	0.57
2031	2,257,793.06	0.59	2,129,716.31	0.56
2032	2,381,699.14	0.58	2,237,782.32	0.56
2033	2,513,039.59	0.58	2,352,332.28	0.55

Table 6.30 Qantas CO_2 emissions profile

	6% per annum 12 year		2% per annum 12 year	
Year	Tot CO_2 (t)	g/kg-km	Tot CO_2 (t)	g/kg-km
2012	3,378,303.70	0.73	3,378,303.70	0.73
2013	3,449,114.40	0.71	3,449,114.40	0.71
2014	3,478,393.83	0.67	3,478,393.83	0.67
2015	3,630,171.61	0.66	3,630,171.61	0.66
2016	3,791,056.06	0.65	3,791,056.06	0.65
2017	3,550,962.53	0.58	3,550,962.53	0.58
2018	3,730,351.08	0.57	3,728,961.25	0.57
2019	3,920,502.95	0.57	3,917,639.89	0.56
2020	4,122,063.92	0.56	4,117,639.25	0.56
2021	4,335,718.56	0.56	4,311,807.03	0.55
2022	4,562,192.47	0.56	4,517,624.87	0.54
2023	4,802,254.82	0.55	4,735,791.79	0.54
2024	5,056,720.90	0.55	4,967,048.72	0.53
2025	5,326,454.96	0.55	5,212,181.07	0.53
2026	5,612,373.05	0.55	5,472,021.36	0.53
2027	5,915,446.23	0.54	5,747,452.07	0.52
2028	6,236,703.81	0.54	6,039,408.62	0.52
2029	6,577,236.83	0.54	6,348,882.56	0.52
2030	6,938,201.84	0.54	6,676,924.94	0.52
2031	7,320,824.75	0.54	7,024,649.86	0.51
2032	7,726,405.03	0.53	7,393,238.27	0.51
2033	8,156,320.13	0.53	7,783,942.00	0.51

Table 6.31 All airlines CO_2 emissions profile

	6% per annum 12 year		2% per annum 12 year	
Year	Tot CO_2 (t)	g/kg-km	Tot CO_2 (t)	g/kg-km
2012	13,108,896.43	0.71	13,108,896.43	0.71
2013	13,425,128.37	0.69	13,425,128.37	0.69
2014	13,220,586.68	0.64	13,016,986.88	0.63
2015	13,842,289.84	0.63	13,638,690.05	0.62
2016	14,501,295.20	0.62	14,297,695.41	0.61
2017	14,789,209.85	0.60	14,585,610.05	0.59
2018	15,522,099.61	0.59	15,310,883.92	0.58
2019	16,298,962.76	0.58	16,079,674.22	0.56
2020	17,122,437.70	0.57	16,894,591.93	0.56
2021	17,995,321.13	0.57	17,335,958.66	0.54
2022	18,920,577.57	0.57	18,189,029.49	0.54
2023	19,901,349.40	0.56	19,093,284.57	0.53
2024	20,940,967.53	0.56	20,051,794.95	0.53
2025	22,042,962.76	0.56	21,067,815.95	0.53
2026	23,211,077.70	0.55	22,144,798.22	0.52
2027	24,449,279.53	0.55	23,286,399.42	0.52
2028	25,761,773.48	0.55	24,496,496.69	0.52
2029	27,153,017.06	0.54	25,779,199.80	0.51
2030	28,627,735.25	0.54	27,138,865.09	0.51
2031	30,190,936.54	0.54	28,580,110.30	0.51
2032	31,847,929.91	0.54	30,107,830.23	0.51
2033	33,604,342.87	0.53	31,727,213.35	0.51

Chapter 7. ICAO's Carbon Offsetting and Reduction Scheme for International Aviation Needs Improvement

Chapter Summary

At the 39th International Civil Aviation Organization (ICAO) Assembly, a global market-based measure in the form of a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was tabled. The scheme covers CO_2 emissions from international aviation post 2020, taking into account special circumstance and capabilities of all States. Any emissions exceeding a baseline level will need to be offset. In this chapter, the CORSIA is applied to a simple example to show that the carbon offset scheme does not reward efficient airlines. An improvement to the CORSIA is recommended that more effectively reward aircraft operators that have attained fuel efficiency goals from 2020.

7.1 Introduction

At the 38th ICAO Assembly, members adopted global aspirational goals of carbon neutral growth from 2020 and 2% annual fuel efficiency improvement for international aviation (ICAO, 2013c). These goals are to be achieved through improvements in airline operations, acquisition of new aircraft technologies, refuelling with sustainable alternative fuels and implementing some global market-based measures (ICAO, 2016a). According to ICAO's Committee on Aviation Environmental Protection (CAEP), the total amount of CO_2 emissions that international aviation will need to offset would be up to 174 million tonnes by 2025 and up to 816 million tonnes by 2040, in order to be carbon neutral after 2020 (ICAO, 2016b; ICAO CAEP, 2016).

The global market-based measure (MBM) presented at the 39th ICAO Assembly in 2016 is a phased implementation of a single global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The pilot and first phase of the CORSIA begins in 2021 and 2024 respectively and over 65 states have volunteered to participate in the pilot phase (ICAO, 2016a, 2016d).

Carbon offset obligations are assigned to aircraft operators operating between participating States. The CORSIA distribute offset obligations based on the aircraft operator's share of the total emissions and success at meeting their individual emissions baseline. In this chapter, an enhancement to the formula used in the CORSIA for distributing offset obligations that takes into consideration an aircraft operator's success at meeting fuel efficiency targets is presented.

7.2 Material and Methods

Paragraph 11 of the 39th ICAO assembly resolution A39-3 defines how CO_2 offsets are calculated for each aircraft operator (ICAO, 2016d) :

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11. Decides that the amount of CO_2 emissions required to be offset by an aircraft operator in a given year from 2021 is calculated every year as follows:
    a) an aircraft operator's offset requirement = [% Sectoral × (an aircraft operator's emissions covered by CORSIA in a given year × the sector's growth factor in the given year)] + [% Individual × (an aircraft operator's emissions covered by CORSIA in a given year × that aircraft operator's growth factor in the given year);
    b) where the sector's growth factor = (total emissions covered by CORSIA in the given year – average of total emissions covered by CORSIA between 2019 and 2020) / total emissions covered by CORSIA in the given year;
    c) where the aircraft operator's growth factor = (the aircraft operator's total emissions covered by CORSIA in the given year – average of the aircraft operator's emissions covered by CORSIA between 2019 and 2020) / the aircraft operator's total emissions covered by CORSIA in the given year;
    d) where the % Sectoral = (100% – % Individual) and;
    e) where the % Sectoral and % Individual will be applied as follows:
        i) from 2021 through 2023, 100% sectoral and 0% individual, though each participating State may choose during this pilot phase whether to apply this to:
            a) an aircraft operator's emissions covered by CORSIA in a given year, as stated above, or
            b) an aircraft operator's emissions covered by CORSIA in 2020;
        ii) from 2024 through 2026, 100 % sectoral and 0% individual;
        iii) from 2027 through 2029, 100 % sectoral and 0% individual;
        iv) from 2030 through 2032, at least 20% individual, with the Council recommending to the Assembly in 2028 whether and to what extent to adjust the individual percentage;
        v) from 2033 through 2035, at least 70% individual, with the Council recommending to the Assembly in 2028 whether and to what extent to adjust the individual percentage;
    f) the aircraft operator's emissions and the total emissions covered by CORSIA in the given year do not include emissions exempted from the scheme in that year;

g) the scope of emissions in paragraphs 11 b) and 11 c) above will be recalculated at the start of each year to take into account routes to and from all States that will be added due to their voluntary participation or the start of a new phase or compliance cycle

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Rewriting paragraph 11 of resolution A39-3 into the mathematical formulas for determining the amount of CO_2 emissions to Offset for aircraft operator x in a given year y from 2021:

$$\mathrm{AO(x,y)} = \underbrace{[\mathrm{w_1 \times E(x,y) \times SG(y)}]}_{Sectoral} + \underbrace{[\mathrm{w_2 \times E(x,y) \times IG(x,y)}]}_{Individual} \quad (7)$$

where

E(x,y) is the emissions covered by the CORSIA for aircraft operator x in year y.

Sector’s Growth Factor in year y is:

$$\mathrm{SG(y)} = \frac{\mathrm{TE(y)} - \overline{\mathrm{TE}}}{\mathrm{TE(y)}} \quad (8)$$

where

TE(y) is the total emissions for the N aircraft operators covered by the CORSIA in year y i.e.

$$\mathrm{TE(y)} = \sum_{i=1}^{N} \mathrm{E(i,y)}$$

$\overline{\mathrm{TE}}$ is the average of the total emissions covered by the CORSIA between 2019 and 2020:

$$\overline{\mathrm{TE}} = \frac{\mathrm{TE(2019)} + \mathrm{TE(2020)}}{2}$$

$\mathrm{TE(y)} - \overline{\mathrm{TE}}$ is the total amount of emissions to be offset in year y.

Aircraft operator’s Growth Factor (i.e. Individual Growth factor) for aircraft operator x in year y is:

$$\mathrm{IG(x,y)} = \frac{\mathrm{E(x,y)} - \overline{\mathrm{E(x)}}}{\mathrm{E(x,y)}} \quad (9)$$

where

$\mathrm{E(x,y)} - \overline{\mathrm{E(x)}}$ is the amount of emissions that aircraft operator x has diverged from its individual baseline emissions level

$\overline{\mathrm{E(x)}}$ is the baseline emissions level, which is the average emissions covered by the CORSIA between 2019 and 2020:

$$\overline{E(x)} = \frac{E(x, 2019) + E(x, 2020)}{2}$$

$$100\% = w_1 + w_2$$

where

$$\% \text{ Sectoral is } w_1 = \begin{cases} 100\%, & 2021 \leq y \leq 2029 \\ 80\%, & 2030 \leq y \leq 2032 \\ 30\%, & 2033 \leq y \leq 2035 \end{cases}$$

$$\% \text{ Individual is } w_2 = \begin{cases} 0\%, & 2021 \leq y \leq 2029 \\ 20\%, & 2030 \leq y \leq 2032 \\ 70\%, & 2033 \leq y \leq 2035 \end{cases}$$

7.3 Enhancement to the CORSIA

Members of ICAO have adopted global aspirational goals of carbon neutral growth from 2020 and 2% annual fuel efficiency improvement for international aviation (ICAO, 2013c). The CORSIA has included each individual aircraft operator's success at meeting the baseline emissions level (which is the average emissions for 2019 and 2020) but fuel efficiency is not included when calculating each aircraft operator's offset obligations. The CORSIA can be improved by also adjusting an aircraft operator's offset obligation based on its success at meeting the target fuel efficiency.

If eff(x,y) is the fuel efficiency of aircraft operator x in year y and effT(y) is the target fuel efficiency in year y then an aircraft operator that is more fuel efficient than the target fuel efficiency would emit less emissions than if it had operated at the target fuel efficiency level i.e.

$E(x,y) < eE(x,y)$

where

eE(x,y) is the estimated amount of emissions generated if all aircraft operator x's flights are flying at the target fuel efficiency.

If all flights from the N aircraft operators covered by the CORSIA are operating at the target fuel efficiency then the total estimated emissions generated in year y is:

$$TeE(y) = \sum_{i=1}^{N} eE(i, y)$$

And the total amount of emissions associated with the success or failure to meet the target fuel efficiency in year y is the difference between the total amount of emissions and the total estimated emissions if all flights were operating at the target fuel efficiency, i.e.:

$TE(y) - TeE(y)$

An aircraft operator's relative success or failure at meeting the yearly target fuel efficiency is denoted by the proportion of the total amount of emissions associated with deviating from the target fuel efficiency that the operator is responsible for i.e. Efficiency factor:

$$\frac{E(x,y) - eE(x,y)}{TE(y) - TeE(y)} \tag{10}$$

Since $TE(y) - \overline{TE}$ is the total amount of emissions to be offset in each year, an aircraft operator's share of the yearly offset based on its success or failure at meeting the fuel efficiency target is:

$$\frac{E(x,y) - eE(x,y)}{TE(y) - TeE(y)} \times (TE(y) - \overline{TE}) \tag{11}$$

In the improved offset scheme, the efficiency component denoted by equation (11) is incorporated into the CORSIA denoted by equation (7). The amount of CO_2 emissions to Offset for aircraft operator x in a given year y from 2021 is:

$$AO(x,y) = \underbrace{[w_1 \times E(x,y) \times SG(y)]}_{Sectoral} + \underbrace{[w_2 \times E(x,y) \times IG(x,y)]}_{Individual} + \underbrace{\left[w_3 \times \frac{E(x,y) - eE(x,y)}{TE(y) - TeE(y)} \times (TE(y) - \overline{TE})\right]}_{Efficiency} \tag{12}$$

where

$TE(y) - \overline{TE}$ is the total amount of emissions to be offset

$100\% = w_1 + w_2 + w_3$

w_1 is % Sectoral

w_2 is % Individual

w_3 is % Efficiency

NB:

$TE(y) - TeE(y) \leq 0$ implies that on average the N aircraft operators covered by the CORSIA in year y are more efficient than the target fuel efficiency. In this case w_3 is set to 0%.

7.4 Results and Discussion

In this chapter, fuel efficiency of aircraft operator x i.e. eff(x,y) is defined as the average amount of CO_2 emitted while transporting a kilogram of payload over a kilometre on each of aircraft operator x's flights. A more efficient aircraft operator will emit less CO_2 while transporting each kilogram of payload over a kilometre. Payload is the combined weight of passengers, luggage and cargo. The formula for calculating the estimated amount of emissions eE(x,y) is :

$$eE(x,y) = effT(y) \times P(x,y) \times D(x,y) \times F(x,y) \tag{13}$$

where

effT(y) is the target efficiency for year y

P(x,y) is the (average) payload on operator x's flight in year y

D(x,y) is the (average) distance flown by operator x's flight in year y

F(x,y) is the total number of flights for operator x in year y.

To demonstrate how the improved carbon offset scheme denoted by equation (12) allocates offset obligations, consider the following simulated simple example. Assume that the carbon offset scheme covers four (N=4) aircraft operators whose emissions are listed in Table 7.1. Emissions are increasing, decreasing and stable from 2020 onwards for aircraft operators A, B and C respectively. Aircraft operator D has identical emissions to aircraft operator C.

Table 7.1 Emissions for four aircraft operators

CO_2 Emission (kt)	Baseline (Average 2019-2020)	Year Y
Operator A (increasing)	80	130
Operator B (decreasing)	120	100
Operator C (stable)	100	100
Operator D (stable)	100	100
Total Emissions	400	430

All aircraft operators have 500 flights and each flight has an average distance of 8,000km. The average payload on each flight for aircraft operator A, B and C is 32,000kg and for aircraft operator D the payload is 28,000kg. The number of flights, average flight distance and average payload remains unchanged. In year Y (> 2020), aircraft operator A's, B's, C's and D's carbon efficiency is

1.02g/kg-km, 0.78g/kg-km, 0.78g/kg-km and 0.89g/kg-km respectively (Table 7.2) and carbon efficiency target effT(y) is set to 0.82g/kg-km.

Table 7.2 CO_2 Efficiency for four aircraft operators

CO_2 Efficiency (g/kg-km)	Year Y
Operator A	1.02
Operator B	0.78
Operator C	0.78
Operator D	0.89

In the improved carbon offset scheme, the weights (w_1, w_2, w_3) in equation (12) are set to (100%, 0%, 0%), (80%, 20%, 0%) and (70%, 20%, 10%) respectively. The CORSIA is equivalent to setting w_3 to 0%.

From 2021 to 2029, the CORSIA will only use the Sectoral factor to allocate offset. This is equivalent to setting weights w_1, w_2, and w_3 in the improved offset scheme to 100%, 0% and 0%, to allocate offset obligations. Aircraft operator B, C and D have identical offset obligations in Table 7.3 even though aircraft operator B's emissions are below its baseline emissions level and aircraft operator C transported more payload than aircraft operator D and is therefore more efficient. This is because the Sectoral factor allocates offset obligations according to each aircraft operator's share of the total emissions for each year.

From 2030 to 2032, the CORSIA will use 80% of the Sectoral and 20% of the Individual factors to allocate offsets. The is equivalent to setting weights w_1, w_2, and w_3 in the improved offset scheme to 80%, 20% and 0% respectively. In Table 7.1, aircraft operator A's emissions are above its baseline level in year Y and the CORSIA will penalise aircraft operator A's by increasing operator A's offset obligations from 9.06kt to 17.26kt in Table 7.3. In year Y, aircraft operator B's emissions are below its baseline level and the CORSIA rewards aircraft operator B with lower offset obligations. Aircraft operator B's offset obligations has dropped from 6.98kt to 1.58kt in Table 7.3. In year Y, both operators C and D's emissions are equal to their baseline emissions level and since the weight w_1 is set to 80% their offset obligations are reduced by 20% from 6.98kt to 5.58kt in Table 7.3. In summary, with weights w_1, w_2, and w_3 set at 80%, 20% and 0%, the CORSIA adjusts the offset obligations based on each aircraft operator's share of the total emissions and relative success at meeting their individual baseline emission level. Since the weight w_3 is set to zero, aircraft operator C and D's offset obligations are identical even though aircraft operator C is more efficient than aircraft operator D.

Table 7.3 Offset obligations for each aircraft operator under CORSIA

Offsets in kt	CORSIA with Weights (100%, 0%, 0%)	CORSIA with Weights (80%, 20%, 0%)
Operator A	9.07	17.26
Operator B	6.98	1.58
Operator C	6.98	5.58
Operator D	6.98	5.58
Total	30.0	30.0

If the weights w_1, w_2, and w_3 are set to 70%, 20% and 10% respectively, the improved carbon offsetting scheme allocate offset obligations based on the operator's share of the total emissions, relative success at staying below the baseline emissions level and relative success at meeting the efficiency target i.e. A combination of the Sectoral, Individual and Efficiency factors. In year Y, aircraft operator C was more efficient than the efficiency target and the improved offset scheme rewards aircraft operator C by reducing its offset obligations from 5.58kt to 4.24kt (Table 7.4), whereas the offset obligations for aircraft operator D was increased from 5.58kt to 5.94kt (Table 7.4), since operator D did not meet the efficiency target . Offset obligations for aircraft operator A are increased from 17.26kt to 19.58kt (Table 7.4) since its year Y emissions are higher than the baseline emissions levels and did not meet the target efficiency. Aircraft operator B's offset obligations are reduced from 1.58kt to 0.24kt since its year Y emissions are lower than the baseline emisions level and surpass the target efficiency.

Table 7.4 Offset obligations for each aircraft operator under improved carbon offset scheme

Offsets in kt	Improved CORSIA with Weights (70%, 20%, 10%)
Operator A	19.58
Operator B	0.24
Operator C	4.24
Operator D	5.94
Total	30.0

7.5 Conclusions and recommendations

Since members of ICAO have adopted global aspirational goals of carbon neutral growth from 2020 and 2% annual fuel efficiency improvement for international aviation, the relative success at attaining these goals need to be incorporated into the formula used in allocating carbon offset obligations. The carbon offsetting and reduction scheme for international aviation (CORSIA) allocates offset obligations to aircraft operators based on Sectoral and Individual factors. The Sectoral approach allocated offset to an aircraft operator relative to its share of the total emissions and Individual approach allocates offsets to an aircraft operator relative to the amount of emissions it diverged from baseline emissions level. The baseline emissions level for each aircraft operator is the average total emissions in 2019 and 2020. The results in this chapter demonstrated that by incorporating the aircraft operator's relative success or failure at meeting fuel efficiency targets, the improved offset scheme provides additional incentive for aircraft operators to be more fuel efficient.

Additional research should be undertaken to determine when (i.e. in which year) and what the weight w_3 of Efficiency factor should be when calculating the carbon offset obligations for each aircraft operator.

Chapter 8. Applying improved carbon offset scheme to Australian international aviation

Chapter Summary

If airlines serving the growth in passenger and cargo traffic in Australian international routes from 2013 to 2033 implemented all the financially viable abatement options where new aircraft are financed at 2% per annum repaid over 12 years, then 31.7Mt of CO_2 will be emitted and 15.2Mt will need to offset in 2033. This chapter shows the difference in the offset obligations calculated by ICAO's CORSIA and the improved carbon offset scheme introduced in Chapter 7 for each airline servicing the Australian international routes from 2021 onwards. The results show that the improved carbon offset scheme would reward efficient airlines such as AirAsia X and Cathay Pacific with lower offset obligations and penalise less efficient airlines such as Etihad with more offset obligations than ICAO's CORSIA.

8.1 Introduction

Between 2013 to 2033, passenger and cargo traffic increased at 6% and 5% per annum respectively and if airlines in Australian international routes implemented all the financially viable abatement options where 90% of the cost of newly acquired aircraft are financed at a yearly rate of 2% and repaid over 12 years then 16.1Mt, 16.9Mt and 31.7Mt of CO_2 are emitted in 2019, 2020 and 2033 respectively. In 2033, airlines will need to offset15.2Mt of CO_2 where the baseline emissions level is the average emissions in 2019 and 2020. (Results in Chapter 6)

This chapter builds on Chapter 6 to determine the offset obligations for each airline using ICAO's CORSIA and the improved carbon offset scheme presented in Chapter 7. This chapter aims to show that the improved offset scheme will provide an additional incentive for airlines servicing Australian international routes to not only reduce their CO_2 emissions but also to improve their CO_2 efficiency.

8.2 Method

In this chapter, it's assumed that all the growth in passenger and cargo traffic from 2013 to 2033 will be serviced by the 14 airlines that are currently servicing the Australian international market in 2012. This will be modelled by distributing the additional fleet of fuel efficient small, medium and long haul aircraft acquired to handle the increase in passenger and cargo traffic (in Chapter 6) amongst these 14 airlines (Yin et al., 2015; Yin et al., 2016). This distribution will be proportional to each airline's share of the total short, medium and long haul payload in 2012.

In the improved carbon offset scheme (i.e. equation (12) in Chapter 7), the target efficiency from 2021 is set to the average CO_2 efficiency in 2019 and 2020 with successive target efficiency set to improve at 2% per annum.

8.3 Scenarios

Three scenarios will be considered.

In the first two scenarios, ICAO's CORSIA will allocate offsets where the weights (w_1, w_2, $w_{3)}$ in equation (12) are set to (100%, 0%, 0%) and (80%, 20%, 0%). With weights w_1, w_2, and w_3 set to 100%, 0%, and 0%, offset obligations in each year is allocated based on only the Sectoral factor (i.e. equation (8)). With weights w_1, w_2, and w_3 set to 80%, 20% and 0%, offset obligations in each year are allocated based on Sectoral and Individual factors (i.e. equation (8) and (9)).

Finally the third scenario highlights the improved offset scheme where the weights w_1, w_2 and w_3 in equation (12) is set 70%, 20% and 10% respectively. This will allocate offset obligations to each airline in each year based on Sectoral, Individual and Efficiency factors (i.e. equation (8), (9) and (10)).

Under CORSIA, Sectoral and Individual factor will be used for calculating offset obligation from 2030 onwards but in this chapter all three scenarios, will allocate offset starting in 2021 to highlight the difference in offset allocations.

8.4 Results

8.4.1 CO_2 Emissions Profile

The new aircraft acquired for fleet renewal and traffic growth will greatly improve the efficiency of the least efficient airlines in 2012 but will have less effect on airlines that are early adopters of more fuel efficient technology or practises and are already fairly efficient such as AirAsia X and Cathay Pacific (Table 8.1). In 2021, the efficiency of Emirates, Delta, Etihad and United all show a big improvement when compared 2020, this is because in 2021 777Xs replaced all 777 long haul flights in the model.

Table 8.1 CO_2 Efficiency from 2012 – 2033 (Summary)

CO_2 Efficiency	Eff(x,2012) g/kg-km	Eff(x,2019) g/kg-km	Eff(x,2020) g/kg-km	Eff(x,2021) g/kg-km	Eff(x,2033) g/kg-km
AirAsia X	0.59	0.46	0.46	0.46	0.46
Cathay	0.60	0.47	0.47	0.47	0.47
Air NZ	0.67	0.55	0.55	0.53	0.49
Singapore	0.65	0.54	0.53	0.52	0.49
Jetstar	0.71	0.56	0.55	0.55	0.50
Virgin	0.73	0.65	0.64	0.63	0.55
Qantas	0.73	0.56	0.56	0.55	0.51
Malaysia	0.72	0.54	0.54	0.52	0.49
Emirates	0.73	0.62	0.62	0.55	0.51
Hawaiian	0.75	0.55	0.54	0.54	0.51
Delta	0.82	0.75	0.75	0.62	0.58
Garuda	0.90	0.63	0.62	0.61	0.54
Etihad	0.87	0.79	0.78	0.73	0.64
United	0.98	0.68	0.68	0.57	0.55
Average	0.71	0.57	0.57	0.54	0.51

With the introduction of 777Xs in 2021 to handle the growth in long haul traffic and to replace all 777 flights to and from Australia, some airlines will see emissions drop below 2020 levels even with the growth in passenger and freight traffic. For example Delta, Emirates and United use 747s and 777s extensively on their 2012 Australian routes and all three airlines show a drop in emissions in 2021 even with the growth in traffic (Table 8.2). Emissions will drop for another year before emissions continue to rise due to the increase in passenger and cargo traffic.

Table 8.2 CO_2 Emissions from 2012-2033 (Summary)

	E(x,2012) (t)	E(x,2019) (t)	E(x,2020) (t)	E(x,2021) (t)	E(x,2033) (t)
AirAsia X	344,078.45	398,333.84	420,879.96	444,778.86	872,142.12
Cathay	1,134,113.79	1,313,693.96	1,387,344.17	1,465,413.40	2,861,458.00
Air NZ	543,549.59	689,831.04	722,233.30	746,234.85	1,360,421.83
Singapore	1,636,828.03	2,059,707.26	2,159,121.10	2,248,180.48	4,132,576.35
Jetstar	530,579.78	617,134.18	644,927.15	674,387.70	1,201,205.25
Virgin	898,027.53	1,216,946.82	1,277,413.31	1,334,341.13	2,352,332.28
Qantas	3,378,303.70	3,917,639.89	4,117,639.25	4,311,807.03	7,783,942.00
Malaysia	744,833.13	853,132.34	895,617.02	919,702.44	1,725,002.50
Emirates	1,784,305.20	2,524,253.39	2,662,295.23	2,595,975.33	4,900,702.83
Hawaiian	130,663.72	133,149.48	138,952.05	145,102.78	255,090.99
Delta	242,331.69	327,757.35	343,876.36	319,552.79	577,940.63
Garuda	301,477.65	302,430.40	313,107.36	324,424.94	526,807.48
Etihad	776,724.89	1,036,918.09	1,085,967.88	1,126,970.90	1,913,239.30
United	663,079.30	688,746.18	725,217.78	679,086.04	1,264,351.79
Total	13,108,896.43	16,079,674.22	16,894,591.93	17,335,958.66	31,727,213.35

8.4.2 Offset obligations

Delta and Garuda emits approximately the same amount of CO_2 emissions in 2021 and under ICAO's CORSIA based on only Sectoral factor (i.e. with w_1, w_2, and w_3 set to 100%, 0% and 0% respectively) both airlines have similar offset obligations of 15.6 and 15.9kt (Table 8.3) even though Delta has less emissions in 2021 than the baseline which is the average emission in 2019 and 2020.

If both Sectoral and Individual factors (i.e. with w_1, w_2, and w_3 set to 80%, 20% and 0% respectively) were taken into consideration in 2021 (instead of 2030), Delta's offset obligations are reduced since it emitted less than its baseline emission level and vice versa for Garuda. Jetstar and United also emits approximately the same amount of emissions in 2021 and if CORSIA with weights w_1, w_2, and w_3 are set to 80%, 20% and 0% in 2021, United will see offset obligations reduced from 33.2kt to 21.0kt since United emitted less than its baseline.

In the model, the target CO_2 efficiency improves at 2% per annum from 2021onwards and in 2021; the target CO_2 efficiency is initialised to 0.57g/kg-km which is the average efficiency in 2019 and 2020. Airlines achieve different carbon efficiencies for the short, medium and long haul flights, for example Emirates operates very CO_2 efficient medium and long haul flights but some of the least CO_2 efficient short haul flights due to low payload in 2012 (Yin et al., 2015). AirAsia X and Cathay

Pacific were two of the most efficient airlines in 2012 and in the model, both airlines continue to lead the pack for the next 20 years but the least efficient airlines such as United, Garuda and Etihad will see the most improvements (Table 8.1) with the addition of new efficient aircraft into its fleet (Yin et al., 2015).

Under the improved carbon offset scheme where weights w_1, w_2, and w_3 is set to 70%, 20% and 10% respectively, efficient airlines will be rewarded with reduced offset obligations and vice versa.

In 2021, Cathay Pacific emitted more emissions than Virgin Australia and under CORSIA (i.e. weights w_1, w_2, and w_3 set to 100%, 0% and 0% or 80%, 20% and 0%), Cathay's offset obligation is also more than Virgin's even though Cathay is one of the most carbon efficient airlines (Table 8.3). Under the improve carbon offset scheme where w_1, w_2, and w_3 is set to 70%, 20% and 10% respectively, Cathay Pacific will be rewarded with lower offset obligations than Virgin Australia. AirAsia X is the most efficient and would also receive lower offset obligations from the improved carbon offset scheme. In 2021, Etihad is the least efficient followed by Virgin, Delta and Garuda (Table 8.1) and offset obligations are increased under the improved carbon offset scheme for all 4 airlines.

In 2021, the target efficiency is 0.57g/kg-km and both Qantas and Emirates attained an average efficiency of 0.55g/kg-km for all their flights but both were penalised with more offset obligations instead of rewarded with less. This inconsistency is because the efficiency factor (equation (10)) in the improved offset scheme calculates offset obligations for Emirates and Qantas based on each airline's average flight distance (equation (13) in Chapter 7). Emirates and Qantas have international flights than range from 2,000km to over 12,000km and the Efficiency factor in the improved carbon offset scheme underestimated the amount of emissions generated if each airline's flights are operating at the target efficiency (i.e. underestimated eE(x,y)).

Table 8.3 Offset obligations in 2021

Offsets in 2021	CORSIA (100%, 0%, 0%) (t)	CORSIA (80%, 20%, 0%) (t)	Improved scheme (70%, 20%, 10%) (t)
AirAsia X	21,777.84	24,456.66	18,835.95
Cathay Pacific	71,751.46	80,380.04	58,645.81
Air NZ	36,538.11	37,271.03	32,885.34
Singapore	110,078.31	115,815.91	105,517.79
Jetstar	33,020.24	35,087.60	34,934.49
Virgin	65,333.73	69,699.20	84,065.43
Qantas	211,120.26	227,729.70	254,778.24
Malaysia	45,031.66	45,090.88	38,551.14
Emirates	127,107.50	102,226.20	102,784.91
Hawaiian	7,104.71	7,494.17	6,304.76
Delta	15,646.36	9,264.27	9,393.47
Garuda	15,884.91	16,039.14	17,005.33
Etihad	55,180.20	57,249.75	64,312.92
United	33,250.29	21,021.04	20,810.00
Total	848825.59	848825.59	848825.59

In 2033, the CO_2 efficiency target is 0.45g/kg-km and all 14 airlines fail to meet the efficiency target (Table 8.1). The improved carbon offset scheme with w_1, w_2, and w_3 set to 70%, 20% and 10% respectively would allocate the 10% (w_3) of the total emissions to be offset according to each airlines relative “failure” at meeting this target CO_2 efficiency.

Table 8.4 Offset obligations in 2033

Offsets in 2033	CORSIA (100%, 0%, 0%) (t)	CORSIA (80%, 20%, 0%) (t)	Improved scheme (70%, 20%, 10%) (t)
AirAsia X	418,931.09	427,651.91	405,876.53
Cathay Pacific	1,374,493.53	1,401,782.61	1,294,043.05
Air NZ	653,474.91	653,657.86	616,645.42
Singapore	1,985,071.76	1,992,689.84	1,943,133.86
Jetstar	576,995.66	575,631.44	567,773.97
Virgin	1,129,936.38	1,124,979.55	1,196,349.76
Qantas	3,738,995.28	3,744,456.71	3,871,219.62
Malaysia	828,600.24	833,005.75	801,791.16
Emirates	2,354,039.22	2,344,717.08	2,390,366.67
Hawaiian	122,532.26	121,833.85	115,066.53
Delta	277,612.20	270,514.52	269,639.46
Garuda	253,050.53	246,248.15	246,318.58
Etihad	919,019.27	905,574.68	925,729.87
United	607,327.93	597,336.31	596,125.79
Total	15,240,080.27	15,240,080.27	15,240,080.27

The offset obligations for all 14 airlines from 2021 to 2033 are presented in Table 8.5 to Table 8.18 (in section 8.6).

8.5 Conclusion

In this chapter, the improved carbon offset scheme presented in Chapter 7 is applied to the 14 airlines that accounted for 72% of all international passengers into and out of Australia in 2012. These airlines will implement all the financially viable abatement options to reduce the growth in emissions over the next 20 s with new aircraft acquisition financed at 2% per annum over 12 years. To attain the aspirational goal of carbon neutral growth from 2021, CORSIA and the improved carbon offset scheme will determine the carbon offset obligations for each airline from 2021 onwards.

The results show that ICAO's CORSIA should take into consideration Individual factors in calculating carbon offset from 2021 so as to provide additional incentive for airlines to emit less and reward airlines that have attained carbon neutral growth instead of waiting till 2030. The results also show that CO_2 efficient airlines will not be rewarded for their efforts under the ICAO's CORSIA. By incorporating CO_2 efficiency targets, the improved carbon offset scheme provides an additional incentive for airlines to not only emit less but also be more CO_2 efficient. Since the target CO_2 efficiency is defined as the amount of CO_2 emitted for each kilogram of payload flown over a kilometre, airlines have the freedom to choose the most appropriate abatement option such as fuel efficient technologies, operational changes and biofuels.

Our results show that additional study is required to determine what the combination of Sectorial, Individual and Efficiency factors (i.e. weights w_1, w_2, and w_3) should be and in which year these factors should be phased in when calculating offset obligations. Additional study is also required to determine if using multiple CO_2 efficiency targets and/or average flight distance for short-, medium- and long-haul routes would improve the consistency of the efficiency factor in the offset allocation formula denoted by equation (10) in Chapter 7. Multiple CO_2 efficiency targets can also be used to differentiate between countries with mature aviation markets, routes with high payload and developing nations with inefficient airlines that service routes to and from Australia.

8.6 Supplementary data

Table 8.5 Air Asia X's carbon offset obligations for servicing Australian international routes from 2021 to 2033

	Air Asia X		
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	21777.84	24456.66	18835.95
2022	43987.03	47290.58	37689.66
2023	67833.52	71738.33	59104.63
2024	93406.84	97889.78	82930.73
2025	120801.72	125840.05	109092.41
2026	150118.51	155689.90	137566.09
2027	181463.48	187546.08	168366.13
2028	214949.25	221521.72	201535.82
2029	250695.23	257736.74	237141.55
2030	288828.00	296318.29	275268.90
2031	329481.85	337401.22	316020.09
2032	372799.18	381128.53	359512.29
2033	418931.09	427651.91	405876.53

Table 8.6 Cathay Pacific's carbon offset obligations for servicing Australian international routes from 2021 to 2033

	Cathay Pacific		
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	71,751.46	80,380.04	58,645.81
2022	144,857.62	155,415.64	117,502.29
2023	223,291.34	235,706.33	184,762.78
2024	307,345.38	321,545.90	259,957.23
2025	397,329.58	413,245.38	342,848.60
2026	493,572.07	511,134.22	433,363.13
2027	596,420.43	615,561.44	531,546.89
2028	706,243.03	726,896.97	637,538.06
2029	823,430.37	845,532.94	751,548.67
2030	948,396.48	971,885.09	873,852.65
2031	1,081,580.49	1,106,394.32	1,004,777.82
2032	1,223,448.15	1,249,528.18	1,144,700.68
2033	1,374,493.53	1,401,782.61	1,294,043.05

Table 8.7 Air NZ's carbon offset obligations for servicing Australian international routes from 2021 to 2033

	Air New Zealand		
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	36538.11	37271.03	32885.34
2022	73229.62	73905.67	65793.21
2023	112094.87	112716.19	101197.65
2024	153265.10	153833.79	139164.74
2025	196879.39	197397.54	179784.82
2026	243085.22	243554.85	223167.66
2027	292038.91	292462.00	269439.74
2028	343906.13	344284.63	318742.56
2029	398862.54	399198.35	371231.78
2030	457094.30	457389.26	427076.76
2031	518798.75	519054.65	486460.50
2032	584185.05	584403.63	549579.77
2033	653474.91	653657.86	616645.42

Table 8.8 Singapore Airline's carbon offset obligations for servicing Australian international routes from 2021 to 2033

	Singapore Airlines		
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	110078.31	115815.91	105517.79
2022	220807.52	226739.55	208878.51
2023	338275.32	344394.49	320513.96
2024	462883.33	469182.44	440434.51
2025	595057.20	601529.16	568787.96
2026	735248.09	741885.96	705823.37
2027	883934.21	890731.18	851868.88
2028	1041622.45	1048571.88	1007318.00
2029	1208850.12	1215945.54	1172621.08
2030	1386186.78	1393421.88	1348280.07
2031	1574236.20	1581604.84	1534845.57
2032	1773638.37	1781134.61	1732915.32
2033	1985071.76	1992689.84	1943133.86

Table 8.9 Jetstar's carbon offset obligations for servicing Australian international routes from 2021 to 2033

		Jetstar	
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	33020.24	35087.60	34934.49
2022	66022.50	67735.04	67255.55
2023	100831.81	102202.86	101273.88
2024	137561.54	138604.24	137137.81
2025	176331.96	177059.23	174991.71
2026	217270.59	217695.11	214979.99
2027	260512.66	260646.84	257249.81
2028	306201.53	306057.49	301953.02
2029	354489.15	354078.70	349247.57
2030	405536.55	404871.22	399298.71
2031	459514.40	458605.38	452279.99
2032	516603.56	515461.68	508374.15
2033	576995.66	575631.44	567773.97

Table 8.10 Virgin Australia's carbon offset obligations for servicing Australian international routes from 2021 to 2033

		Virgin Australia	
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	65333.73	69699.20	84065.43
2022	130496.72	133898.29	158942.80
2023	199099.30	201573.17	235210.90
2024	271361.27	272943.14	313600.45
2025	347515.87	348240.83	394709.94
2026	427810.50	427712.99	479054.38
2027	512507.50	511621.23	567096.32
2028	601885.00	600242.90	659266.36
2029	696237.78	693871.99	755977.20
2030	795878.28	792820.07	857633.64
2031	901137.56	897417.30	964639.99
2032	1012366.38	1008013.56	1077405.67
2033	1129936.38	1124979.55	1196349.76

Table 8.11 Qantas's carbon offset obligations for servicing Australian international routes from 2021 to 2033

Year	Qantas CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	211120.26	227729.70	254778.24
2022	422701.47	438158.24	485006.79
2023	646415.28	660762.67	723299.70
2024	883005.70	896286.39	971434.09
2025	1133261.68	1145517.65	1230934.21
2026	1398019.72	1409292.13	1503172.70
2027	1678166.58	1688495.77	1789435.32
2028	1974642.34	1984067.68	2090964.24
2029	2288443.43	2297003.34	2408988.07
2030	2620625.99	2628357.86	2744743.75
2031	2972309.41	2979249.59	3099493.04
2032	3344680.06	3350863.79	3474535.57
2033	3738995.28	3744456.71	3871219.62

Table 8.12 Malaysia Airline's carbon offset obligations for servicing Australian international routes from 2021 to 2033

Year	Malaysia Airlines CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	45031.66	45090.88	38551.14
2022	90520.48	91029.09	79663.34
2023	138957.85	139898.98	124681.96
2024	190514.41	191871.41	173539.01
2025	245370.94	247127.46	226244.41
2026	303718.99	305858.97	282864.37
2027	365761.56	368269.27	343508.01
2028	431713.78	434573.88	408318.98
2029	501803.74	505001.24	477470.04
2030	576273.20	579793.53	551159.67
2031	655378.52	659207.51	629609.89
2032	739391.47	743515.38	713065.04
2033	828600.24	833005.75	801791.16

Table 8.13 Emirate's carbon offset obligations for servicing Australian international routes from 2021 to 2033

		Emirates	
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	127107.50	102226.20	102784.91
2022	255681.03	232408.51	234756.13
2023	392753.74	371029.57	375997.17
2024	538813.16	518577.77	526739.46
2025	694375.67	675570.47	687324.76
2026	859988.35	842555.88	858179.27
2027	1036230.95	1020114.94	1039798.18
2028	1223717.93	1208863.40	1232736.60
2029	1423100.64	1409453.98	1437604.32
2030	1635069.61	1622578.64	1655063.02
2031	1860357.00	1848970.99	1885825.29
2032	2099739.13	2089408.89	2130654.68
2033	2354039.22	2344717.08	2390366.67

Table 8.14 Hawaiian airline's carbon offset obligations for servicing Australian international routes from 2021 to 2033

		Hawaiian Airlines	
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	7104.71	7494.17	6304.76
2022	14186.90	14463.88	12360.82
2023	21639.15	21807.87	18944.78
2024	29485.23	29549.86	26044.29
2025	37750.37	37715.00	33658.47
2026	46461.33	46329.98	41794.68
2027	55646.48	55423.09	50466.59
2028	65335.91	65024.31	59692.88
2029	75561.50	75165.45	69496.50
2030	86357.04	85880.19	79904.09
2031	97758.35	97204.24	90945.64
2032	109803.36	109175.44	102654.37
2033	122532.26	121833.85	115066.53

Table 8.15 Delta's carbon offset obligations for servicing Australian international routes from 2021 to 2033

	Delta Air Lines		
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	15646.36	9264.27	9393.47
2022	31332.78	24876.70	25051.61
2023	47924.29	41397.00	41565.84
2024	65476.23	58880.47	59006.45
2025	84047.27	77385.73	77442.47
2026	103699.63	96974.95	96943.43
2027	124499.25	117714.03	117580.53
2028	146516.04	139672.80	139427.47
2029	169824.10	162925.31	162561.14
2030	194501.98	187550.03	187062.11
2031	220632.92	213630.15	213015.11
2032	248305.16	241253.84	240509.46
2033	277612.20	270514.52	269639.46

Table 8.16 Garuda's airline's carbon offset obligations for servicing Australian international routes from 2021 to 2033

	Garuda		
Year	CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	15884.91	16039.14	17005.33
2022	31478.02	30912.96	32461.27
2023	47655.84	46398.50	48293.82
2024	64463.48	62540.50	64607.12
2025	81948.94	79386.50	81490.94
2026	100163.20	96987.00	99026.47
2027	119160.40	115395.60	117290.06
2028	138997.95	134669.13	136355.68
2029	159736.69	154867.83	156296.64
2030	181441.07	176055.50	177186.82
2031	204179.33	198299.72	199101.62
2032	228023.68	221672.03	222118.70
2033	253050.53	246248.15	246318.58

Table 8.17 Etihad's carbon offset obligations for servicing Australian international routes from 2021 to 2033

Year	Etihad CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	55180.20	57249.75	64312.92
2022	109808.45	110273.87	122131.90
2023	166931.89	165853.45	181170.61
2024	226722.61	224159.69	241939.64
2025	289363.38	285374.41	304862.18
2026	355048.25	349690.52	370306.94
2027	423983.06	417312.68	438609.15
2028	496386.07	488457.85	510084.38
2029	572488.62	563356.03	585038.09
2030	652535.82	642250.90	663772.44
2031	736787.33	725400.63	746591.37
2032	825518.09	813078.69	833804.41
2033	919019.27	905574.68	925729.87

Table 8.18 United Airline's carbon offset obligations for servicing Australian international routes from 2021 to 2033

Year	United Airlines CORSIA (100%, 0%, 0%)	CORSIA (80%, 20%, 0%)	Improved scheme (70%, 20%, 10%)
2021	33250.29	21021.04	20810.00
2022	66786.28	54788.40	54402.52
2023	102447.30	90672.09	90133.80
2024	140357.61	128796.51	128126.33
2025	180648.90	169293.48	168509.99
2026	223460.69	212302.69	211422.67
2027	268940.88	257972.20	257010.73
2028	317246.21	306458.95	305429.55
2029	368542.83	357929.28	356844.07
2030	423006.89	412559.55	411429.39
2031	480825.13	470536.69	469371.32
2032	542195.51	532058.90	530867.04
2033	607327.93	597336.31	596125.79

Chapter 9. Conclusion

9.1 Overview

For a geographically isolated nation such as Australia, there are very few alternative transport options other than aviation that can transport both passengers and freight internationally in a timely manner. International aviation emissions were excluded from Kyoto protocol and UNFCCC COP21, and ICAO was tasked to work with member states and industry groups in limiting and reducing international aviation emissions. Members of ICAO have committed to the aspirational goal of carbon neutral growth and 2% fuel efficiency improvement from 2020. At the 39th ICAO assembly in 2016, a global market-based measure for reducing international aviation emissions was tabled for implementation in 2021. To attain the aspiration goals, the global MBM will join other emissions mitigation measures namely sustainable fuels, and more efficient aircraft operations and aircraft technologies.

Chapter 2 gives some background and highlights how governments have directly and indirectly influenced the development of the aviation industry. By knowing the CO_2 emissions profile of airlines serving Australian international routes, the financial viability of emissions abatement options and the equitableness of the ICAO global MBM, this thesis identify additional environmental policy instruments that encourage airlines to emit less CO_2 and be more productive.

Chapter 4 presents the CO_2 emissions profile for the 14 airlines that carried 72% of all international passengers into and out of Australia in 2012. Airline performance metrics such as available seat mile, revenue passenger kilometre, cost per seat mile, passenger load factor, fuel cost per passenger, fuel consumption per seat mile and many others focus on an airline's performance with respect to the number of passengers, number of seats or weight of freight separately. C Miyoshi and Merkert (2015) defines an airline's carbon efficiency as the amount of CO_2 emitted per available tonne-kilometre (ATK), where ATK is the available weight capacity for transporting passengers, freight and mail. Airlines with a more fuel-efficient fleet of aircraft will most likely have a lower CO_2 per ATK, but this definition of carbon efficiency does not take into consideration the actual number of passengers, freight and/or mail that was transported (i.e. the utilised capacity). In this thesis, the airline's fuel/CO_2 efficiency metric is defined as the CO_2 emitted for transporting the combined weight of passengers, luggage and freight (including mail) over a kilometre (i.e. grams of CO_2 emitted per kilogram-kilometre). An airline's emissions profile is the total CO_2 emissions, the amount of CO_2 emissions for transporting a passenger over one kilometre and the amount of CO_2 emissions for transporting a kilogram of payload over one kilometre. In 2012, 13.1 Mt of CO_2

emissions were generated at a carbon efficiency of 75.7 grams of CO_2 per passenger-kilometre (75.7g/pax-km) or 0.71 grams of CO_2 per kg of payload-kilometre (0.71g/kg-km). The results highlight the importance of freight when calculating the airlines carbon efficiency, where traditional network carriers such as Cathay Pacific can match the efficiency of a low-cost airline such as AirAsia X by transporting more cargo and fewer passengers while flying the same type of aircraft. In 2012, both airlines attain carbon efficiency of 0.6 g of CO_2 per kg-km. Emirates exercising their 5^{th} freedom traffic rights between Australia and New Zealand has a low load factor, leading to low CO_2 efficiency. Short-haul flights account for almost 60% of the international flight, but only around 20% of the emissions at 2.6 Mt. The results show that, due to Australia's geographic isolation, selecting the "right" aircraft on long- and medium-haul routes can greatly reduce the total emissions and airlines can improve their carbon efficiency by emitting less and/or by increasing their payload. Australian airlines account for just over a third of all emissions, with Qantas responsible for just over a quarter of all emissions. These findings answer research question 1 "What is the CO_2 emissions profile of airlines operating in the Australian international routes?"

Chapter 5 builds on Chapter 4 by modelling the change in the CO_2 emissions profile as passengers and cargo traffic grows at 6% and 5% per annum respectively between 2013 and 2033. Airlines will implement a number of abatement options to curb the growth in CO_2 emissions and the analysis show that, by acquiring the latest and more efficient aircraft, 17.2 Mt and 32.1 Mt of CO_2 would be emitted in 2020 and 2033 respectively. By increasing the load factor by 10% and combining flights together, CO_2 emissions will grow at 6.1% per annum with 15.6Mt and 29.2Mt emitted in 2020 and 2033. Carbon efficiency has also improved from 0.71g of CO_2 per kg-km to 0.56g/kg-km in 2020 and 0.49g/kg-km in 2030. Airlines flying in Australian international routes will need additional abatement options in orders to stay carbon neutral after 2020 and not all of these abatement options are financially viable.

Chapter 6 determines the acquisition, installation, maintenance and fuel cost associated with the abatement options presented in Chapter 5 over the remaining life of each aircraft for each airline. Because non-Australia-based airlines will utilise only a small fraction of their fleet to service the Australian market, a MACC was produced that combined all the foreign carriers' aircraft used on Australian routes. MACCs for each of the three Australian-based airlines are also presented. Even though, acquiring new fuel-efficient aircraft will reduce the most emissions, this option is only financially viable if aircraft are purchased on favourable financial terms. If aircraft purchase is financed at 6% per annum and repaid over 12 years, and airlines implement all the financially viable abatement options, airlines flying into and out of Australia will emit 33.6 Mt of $CO_{2,}$ with a CO_2 efficiency of 0.53 g/kg-km in 2033. The amount of CO_2 emitted will drop to 31.7 Mt with a

CO_2 efficiency of 0.46 g/kg-km if new aircraft purchases are financed at 2% per annum. In Chapter 5, if the load factor on each flight was increased by 10% and flights are bundled together, an additional 3.1Mt CO_2 can be reduced by 2033. According to Brueckner and Zhang (2010), charging for emissions will increase airfares, improve aircraft fuel efficiency, reduce flight frequency and increase passenger load factor. The increase in ticket price as a result of airlines passing the environmental cost to passengers can affect travel demand, as can pandemics and changes to GDP (Boeing, 2012a, 2016; Liu, Moss, & Zhang, 2011; Pagoni & Psaraki-Kalouptsidi, 2016). Because the change in passenger load factor depends on many factors (such as airfares, economy, security concerns, pandemics, frequent flyer programs) it is unclear what the abatement cost for increasing load factor will be, and so it was excluded from the costing model used to produce these four MACCs.

These findings (in Chapter 5 and 6) answer research question 2: "What emissions abatement options are available to airlines on Australian international routes and what is the impact on the future CO_2 emissions profile? What are the marginal abatement costs and what is the impact of low-interest finance?"

Chapter 7 reviews the CORSIA that was tabled at the 39th ICAO Assembly in 2016, and presented an improved carbon offset scheme. Members of ICAO have adopted the aspirational goals of carbon neutral growth and 2% fuel efficiency improvements from 2020 onwards. The CORSIA distributes offset obligations based on a combination of sectoral and individual factors. For each airline, the sectoral factor is the proportion of the total emission that each airline is responsible for, and the individual factor is an airline's relative success or failure at meeting its baseline emissions level (where the baseline emissions level is the average of emissions in 2019 and 2020). The CORSIA does not take into consideration each airline's relative success or failure at attaining the 2% fuel efficiency improvements. In Chapter 4, carbon efficiency is defined as the amount of CO_2 emitted in order to fly each kilogram of payload over one kilometre. CO_2 efficiency can be improved by reducing emissions on each flight, which can involve upgrading the aircraft/aircraft technology, flying more efficiently or refuelling with biofuel. CO_2 efficiency can also be improved by increasing the payload on each flight where payload is defined as the combined weight of the passengers, luggage and freight. The improved carbon offset scheme also rewards carbon efficient airlines with reduced offset obligations if the airline surpasses or meets the yearly CO_2 efficiency target and vice versa.

In Chapter 8, the CORSIA and the improved carbon offset scheme presented in Chapter 7 are applied to the airlines servicing Australian international routes to determine each airline's carbon offset obligations. The 14 airlines studied in Chapter 4 would acquire new aircraft to service all the growth in passenger and cargo traffic. If the airlines implemented all the financially viable abatement options, financed the acquisition of new aircraft at 2% per annum repaid over 12-year period, and set the 2021 CO_2 efficiency target to be the average CO_2 efficiency in 2019 and 2020, with the target improving at a yearly rate of 2%, then 848.8 kt and 15.2 Mt of CO_2 will need to be offset in 2021 and 2033, respectively. The results showed that the CORSIA does not reward efficient airlines such as AirAsia X and Cathay Pacific that are early adopters of fuel-efficient technologies or practices. The improved carbon offset scheme where sectoral, individual and efficiency factors are weighted at 70%, 20% and 10%, respectively, would reward these efficient airlines with lower offset obligations. These results show that by incorporating CO_2 efficiency target into the CORSIA, airlines have an additional incentive not only to emit less but also to be more CO_2 efficient.

The results presented in Chapters 7 and 8 thus answer research question 3 “What integrative policies could facilitate more effective emissions outcomes on the Australian international routes?”

9.2 Policy implications

The results provide policy makers with a snapshot of the CO_2 emission profiles (both quantity and efficiency) of airlines servicing Australian international routes in 2012 and estimated the change in emissions profile as airlines implement a number of abatement options over the next 20 years. This thesis has the following implications for policy makers:

- Policy makers should consider performance standards that allow airlines the freedom to choose the most appropriate means of meeting their commitments. In this thesis the airline’s CO_2 emitted for transporting the combined weight of passengers, luggage and freight (including mail) over one kilometre (i.e. grams of CO_2 emitted per kilogram kilometre) provides a fairer assessment of an airline’s fuel/CO_2 efficiency, irrespective of the airline’s business model, revenue, ATK or equipment used. Setting a fuel/CO_2 efficiency target based on this metric would allow airlines the flexibility to choose more fuel-efficient equipment, increase payload and/or increase flight distance so as to meet this efficiency target.
- Policy makers should consider incorporating CO_2 efficiency targets into the ICAO’s CORSIA. This will provide airlines with additional incentives to be more CO_2 efficient.
- The cost of emissions abatement options in aviation can be high, and policy makers should consider an aviation “green” credit agency similar to export credit agencies to assist in financing the acquisition and implementation of these abatement options. (However additional research will be needed because government intervention in the credit market would be welcome by airlines that benefit the most from the intervention but could be seen

as “government welfare” if the intervention involve the use of public funds. By producing MACCs for each airline, policy makers can determine which airlines benefit the most and least, and also identify likely source of objections to such an intervention. Arul (2014) presented four methods to raise funds from passengers and airlines for emissions reduction projects. These methods “monetise” GHG emissions which takes into consideration load factors and emissions per passenger-mile).

9.3 Limitations

There are limitations to this research. Mostly these relate to the high traffic growth rate in the Asia-Pacific region, the input data that was used in the emission model and costing model, and also to some of the assumptions and data used when constructing these models.

Because the Asia-Pacific region is experiencing some of the highest growth in air travel, the number of airlines, flights, routes and international passengers into and out of Australia, and the resultant emissions profile, will change (Air Transport Action Group (ATAG), 2016). In Chapter 4, the 2012 airlines emissions profiles excluded flights to and from China (the ninth highest source of passengers to Australia) since China-based airlines did not play a significant role in the Australian international market at that time. In 2016, China became the second highest source of visitors to Australia and will overtake New Zealand in 2017 (Austrade, 2016). In 2012, three major Chinese airlines flew between their respective hubs in Beijing, Shanghai and Guangzhou to and from Australia, but by 2016 this has doubled to six airlines and from 12 Chinese cities (CAPA - Centre for Aviation, 2016). All three major Chinese carriers and their respective hub airports in Beijing, Shanghai and Guangzhou also handle some of the highest volumes of air freight (Woods, 2016a, 2016b).

In Chapter 4, the International airline activity data that was collected and published by the BITRE which was used to determine the emissions profile, showed passenger and freight traffic for each airline flying between Australia and destination country in each month. Ideally, this passenger and freight traffic load should be between each Australian and international city pairs, so as to improve the fidelity of the model. In the model, the weight of each passenger’s luggage is set at 15 kg for short-haul international flight and 25 kg on medium- and long-haul flights. On certain airlines, the complimentary luggage allowance from flights to USA starts at 46kg for each passenger, which is almost double the amount used in the simulation. An increase in passenger luggage can improve CO_2 efficiency, but it could also lower amount of freight that can be carried on each flight.

Abatement options modelled in Chapter 5 were assumed to have no interaction with each other, and implementing one option has no effect on later adoption of other abatement options, and there are no flow-on effects that could affect the passenger and freight growth rate. This, of course, is not accurate; for example, some airlines have retrofitted their aircraft with new light-weight thin seats, which require less space and have allowed airlines to install additional seats. This allowed these airlines to transport additional passengers, thus increasing the payload and improving the CO_2 efficiency on each flight. The model also assumed that all airlines that service Australian international routes could implement or retrofit their fleet with each abatement option in one year. Renewing and retiring an airline's fleet can take many years and will depend on many factors, such as the aircraft manufacturer, traffic growth, fuel cost and maintenance cost. Finally, the model assumes the average distance flown and the average number of seats per flight remains unchanged on all flights over the next 20 years. However, new aircraft models are usually more fuel efficient, may have a better range and have increased payload capacity than the superseded model.

The assumptions and data used to construct aircraft purchase, lease, residual and maintenance cost models in Chapter 6 have a number of limitations. The aircraft purchase cost model assumed that airlines will finance 90% of the aircraft's cost over 12 and 15 years, with aircraft list prices discounted at 40% for the latest generation of aircraft (777X, 737MAX) and 50% for all other aircraft. The actual discounts are very rarely published, and the model estimated the discount based on the published market value of aircraft in the leasing company's portfolios. The exact terms that airlines finance their aircraft purchases are also not publicly available. The aircraft leasing cost model had assumed a fixed lease period of 5 years, with a lease rate factor of 10% per annum, but lease rates and period are dependent on many factors, ranging from aircraft demand, economy, aircraft market value and aircraft age. The residual cost model assumed that all aircraft are straight-line depreciated over 25 years, with a final 10% residual value, and that airlines retire their fleet when aircraft are 25 years old. Airlines serving the Australian market depreciate their fleet over a period of between 15 and 25 years, with some airlines, such as Singapore and Emirates retiring their aircraft earlier than their competitors. The amount airlines receive when an aircraft is disposed is dependent on many factors, including the age of aircraft, availability of new aircraft, passenger growth rate and freight growth rate. Maintenance cost for each aircraft type used in the model were extracted from maintenance cost graphs in the executive commentary by Markou and Cros (2013). The accuracy of the maintenance cost model can be improved by acquiring the raw data used to produce these graphs in the executive commentary. Lost revenue when an aircraft is taken out of service and modification performed was not modelled because this will vary for each airline and route.

9.4 Future research

The intention of this thesis was to provide a better understanding of airlines emissions and airline efficiency and to determine how best to incorporate this knowledge into environmental policy instruments for reducing international aviation emissions.

This sets the stage for further research in the following areas. Chapter 5 showed that the increase in the passenger load on each flight and combining flights led to reduction in the number of flights and emissions and improvements in CO_2 efficiency. Research is required to determine the factors and identify the financial instruments, or other policy instruments, that can be used to increase the passenger load factor and freight on each flight. Chapter 6 showed that favourable finance increased the likelihood that airlines will acquire new aircraft. Further research is needed to investigate "green" financing that can help the aviation industry research, develop and implement additional abatement options to reduce additional emissions from the aviation industry. Chapter 8, showed that the efficiency factor in the improved carbon offset scheme needs further study to remove some inconsistent behaviour. The "right" and/or multiple CO_2 efficiency target should allow airlines the flexible to choose the appropriate abatement options (i.e. technology, airline practice, business model and routes) to improve their emissions profile. Finally, the CORSIA and the improved carbon offset scheme are seeking to offset aviation emissions growth that exceeded the average of 2019 and 2020 emissions level, but offsetting does not decarbonise the aviation industry.

In conclusion, this thesis has shown that Australian long- and medium-haul flights are some of the biggest contributors to CO_2 emissions. Some of the most efficient airlines are already serving these Australian international routes. On some of these routes, freight plays an important component of the total payload and a more accurate measure of an airline's fuel/CO_2 efficiency is to determine the amount of CO_2 emitted for transporting the combined weight of passengers, luggage and freight over each kilometre. Non-Australian carriers exercising their 5^{th} freedom traffic rights on NZ routes are some of the least CO_2 efficient airlines. It is hoped that policy makers can use the results of this thesis to improve the ICAO's CORSIA. Due to the high cost of research, development and implementation of certain abatement options, it is also hoped that policy makers can establish a "green" aviation credit/finance for the aviation industry.

Chapter 10. References

Air New Zealand. (2012a). Air New Zealand invests in B777-200ER upgrade programme. from http://www.airnewzealand.com.au/press-release-2012-airnz-invests-in-b777-200er-upgrade-programme

Air New Zealand. (2012b). Annual Financial Result. from http://www.airnewzealand.com.au/assets/PDFs/2012-annual-financial-report.pdf

Air Transport Action Group (ATAG). (2016). Aviation Benefits Beyond Borders. from http://aviationbenefits.org/media/149668/abbb2016_full_a4_web.pdf

AirAsia. (2012). Annual Report. from http://www.airasia.com/iwov-resources/my/common/pdf/AirAsia/IR/annual-report-2012.pdf

Airbus. (2004). Getting to grips with Fuel Economy. from http://ansperformance.eu/references/library/airbus-fuel-economy.pdf

Airbus (Producer). (2012a). A320 Sharklet Entry into Service. Retrieved from http://www.globalaviationpartners.com/wp-content/uploads/2014/09/p_Sharklet_Entry_into_Service.pdf

Airbus. (2012b). Airbus Global Market Forecast 2012-2031. *Airbus*, 1-64. http://www.airbusgroup.com/dam/assets/airbusgroup/int/en/investor-relations/documents/2012/presentations/2012-31-Global-Market-Forecast/Global+Market+Forecast+2012-2031.pdf

Airbus. (2013). New Airbus aircraft list price for 2013. from http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/new-airbus-aircraft-list-prices-for-2013/

Airbus. (2014a). Airbus Aircraft Families. 2014, from http://www.airbus.com/aircraftfamilies/passengeraircraft/

Airbus. (2014b). Airbus GMF booklet 2014-2033. from http://www.airbus.com/company/market/forecast/

Airbus. (2014c). New Airbus aircraft list prices for 2014. from http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/new-airbus-aircraft-list-prices-for-2014/

Airbus. (2015). New Airbus aircraft list prices for 2015. from http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/new-airbus-aircraft-list-prices-for-2015/

Airbus. (2016a). Global Market Forecast 2016-2035. from http://www.airbus.com/company/market/global-market-forecast-2016-2035/

Airbus. (2016b). Lufthansa takes delivery of the world's first Airbus A320neo as launching customer. http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/lufthansa-takes-delivery-of-the-worlds-first-airbus-a320neo-as-launching-customer/

Aircraft Interior International. (2013). Fibre provider. *Aircraft Interior International*. 2015, from http://www.lumexis.com/press/aix-article-2013-1-31/

Airfleets. (2016). Airlines Fleet. from http://www.airfleets.net/recherche/airline.htm

Alamdari, F. (1999). Airline in-flight entertainment: the passengers' perspective. *Journal of Air Transport Management*, *5*(4), 203-209. doi: http://dx.doi.org/10.1016/S0969-6997(99)00014-9

Alaska Airlines. (2014). Alaska Air Group Sustainability Highlights. *Strategies to Improve Aerodynamics*. from https://www.alaskaair.com/content/about-us/sustainability-report.aspx

http://www.alaskaair.com/content/about-us/sustainability-report/2014-highlights

http://www.prnewswire.com/news-releases/alaska-air-group-reduced-its-emissions-intensity-by-30-percent-over-the-past-10-years-2014-accomplishments-detailed-in-third-annual-sustainability-report-300086201.html

Ali, S., Hampson, N., Inglis, W., Sargeant, A., & Ali, A. (2013). Aviation Finance: Fastern your seatbelts. from https://www.pwc.com/en_GX/gx/aerospace-defence/publications/assets/pwc-aviation-finance-fastern-your-seat-belts-pdf.pdf

Alonso, G., Benito, A., Lonza, L., & Kousoulidou, M. (2014). Investigations on the distribution of air transport traffic and CO2 emissions within the European Union. *Journal of Air Transport Management*, *36*, 85-93. doi: 10.1016/j.jairtraman.2013.12.019

Arul, S. G. (2014). Methodologies to monetize the variations in load factor and GHG emissions per passenger-mile of airlines. *Transportation Research Part D: Transport and Environment*, *32*, 411-420. doi: 10.1016/j.trd.2014.08.018

Ascend. (2013). Lease Rates. from http://www.airliners.net/aviation-forums/general_aviation/read.main/5884179/2/269261039#20

http://www.airliners.net/aviation-forums/general_aviation/read.main/5763316/2/1533312475#39

Ascend (Producer). (2014a). The 100 billion dollar baby! Retrieved from http://www.ascendworldwide.com/download/AscendGlobalWebcast_Feb2014.pdf

Ascend. (2014b). Lease Rates. from http://www.airliners.net/aviation-forums/general_aviation/read.main/5970415/2/1001471833#38

http://www.airliners.net/aviation-forums/general_aviation/read.main/6134182/2/#1

Ascend. (2015). Lease rates. from http://www.airliners.net/aviation-forums/general_aviation/read.main/6360438/2/829350324#58

Asia and Pacific Initiative to Reduce Emissions (ASPIRE). (2012). ASPIRE Annual Report.

Austrade. (2016). International visitors to Australia. from http://www.tra.gov.au/documents/ivs/International_Visitors_in_Australia_June_2016_quarterly_results_of_the_International_Visitor_Survey.html#TopmarketsVisitorsChart

Australian Aviation (Producer). (2012). SIA's Queen bids adieu. *Australian Aviation*. Retrieved from http://australianaviation.com.au/2012/03/sias-queen-bids-adieu/

Australian Aviation (Producer). (2013a). Jetstar Group celebrates 100 aircraft. *Australian Aviation*. Retrieved from http://australianaviation.com.au/2013/04/jetstar-group-celebrates-100-aircraft/

Australian Aviation (Producer). (2013b). Launch customer Air New Zealand gets its first A320 with Sharklets. *Australian Aviation*. Retrieved from http://australianaviation.com.au/2013/06/launch-customer-air-new-zealand-gets-its-first-a320-with-sharklets/

Aviation Partners Boeing. (2015). Aviation Partners Boeing Blended Winglets. Retrieved 24-April, 2015, from http://www.aviationpartnersboeing.com/products.php

Bachman, J., & Schlangenstein, M. (2017). Southwest is launch customer for Boeing 737 MAX but won't get the first delivery, *Seattle Times*. Retrieved from http://www.seattletimes.com/business/southwest-is-launch-customer-for-boeing-737-max-but-wont-get-the-first-delivery/

Backx, M., Carney, M., & Gedajlovic, E. (2002). Public, private and mixed ownership and the performance of international airlines. *Journal of Air Transport Management, 8*(4), 213-220. doi: http://dx.doi.org/10.1016/S0969-6997(01)00053-9

Banbury, J., Behrens, D., Bowell, Q., Campos, N., Cirilo, C., Choi, T. P., . . . Toepoel, V. R. (2009). The IATA Technology Roadmap Report. https://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2009.pdf

Banbury, J., Behrens, D., Browell, Q., Campos, N., Cirilo, C., Markou, C., . . . Stumpf, E. (2009). IATA Technology Roadmap - Technical Annex. https://www.iata.org/whatwedo/environment/Documents/technology-roadmap-annex.pdf

Barker, T., Bashmakov, I., Bernstein, L., Bogner, J. E., Bosch, P. R., Dave, R., . . . Zhou, D. (2007). Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. from http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ts.html

Bazargan, M., & Hartman, J. (2012). Aircraft replacement strategy: Model and analysis. *Journal of Air Transport Management, 25*, 26-29. doi: http://dx.doi.org/10.1016/j.jairtraman.2012.05.001

Bednarek, J. R. (2016). *Airports, Cities and the Jet Age*

US Airports Since 1945 Palgrave Studies in the History of Science and Technology J. Fleming & R. Launius (Eds.),

Berdowski, Z., Broek-Serle, F. N. v. d., Jetten, J. T., Kawabata, Y., Schoemaker, J. T., & Versteegh, R. (2009). *Survey on Standard Weights of Passengers and Baggage* Retrieved from https://www.easa.europa.eu/system/files/dfu/Weight%20Survey%20R20090095%20Final.pdf

Berglund, T. (2008). *Evaluation of Fuel Saving for an Airline.* (Bachelor in Aeronautical Engineering), Malardalen University. Retrieved from http://www.diva-portal.org/smash/get/diva2:121168/FULLTEXT01.pdf (MDH.IDT.FLYG.0188.2008.GN300.15HP.FP)

Bockel, L., Sutter, P., Touchemoulin, O., & Jönsson, M. (2012). Using Marginal Abatement Cost Curves to Realize the Economic Appraisal of Climat Smart Agriculture Policy Options. from http://www.fao.org/docs/up/easypol/906/ex-act_MACC_116EN.pdf

Boeing. (2004). Fuel Conservation Flight Operations Engineering. from http://www.phenom.aero/resources/library/fuel_conservation.pdf

Boeing. (2007). Financing Aircraft. from http://www.boeing.com/resources/boeingdotcom/company/about_bca/pdf/Financing_Options.pdf

Boeing. (2009). 777 Perf Summary. Seattle, USA.

Boeing (Producer). (2012a, Jan 2012). Aviation Policy and Geopolitics 2012. *Boeing*. Retrieved from www.boeing.com/commercial/pdf/geopolitical_trends.pdf

Boeing. (2012b). Boeing Current Market Outlook 2012 *Boeing* (pp. 1-43). Boeing.

Boeing. (2014a). Boeing Commercial Aircraft Chracteristics. 2014, from http://www.boeing.com/boeing/commercial/products.page

Boeing. (2014b). Boeing Current Market Outlook 2014. from http://www.boeing.com/boeing/commercial/cmo/

Boeing. (2015). Airplane Prices. from http://www.boeing.com/company/about-bca/

Boeing. (2016). Current market outlook 2016-2035. from http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/cmo_print_2016_final_updated.pdf

Bognár, V. (2012). *Carbon leakage and distortion of competition between EU and non-EU airlines and hub airports The negative impact of the inclusion of aviation in the EU ETS.* (Master of Arts in European Economic Studies Masters), College of Europe.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., . . . Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres, 118*(11), 5380-5552. doi: 10.1002/jgrd.50171

Borggren, C., Moberg, Å., Räsänen, M., & Finnveden, G. (2013). Business meetings at a distance – decreasing greenhouse gas emissions and cumulative energy demand? *Journal of Cleaner Production, 41*, 126-139. doi: http://dx.doi.org/10.1016/j.jclepro.2012.09.003

Borken-Kleefeld, J., Fuglestvedt, J., & Berntsen, T. (2013). Mode, Load, And Specific Climate Impact from Passenger Trips. *Environ Sci Technol, 47*(14), 7608-7614. doi: 10.1021/es4003718

Braathen, N. A., Philippe Crist, Delzeit, R., Hood, C., Searchinger, T., Eisentraut, A., & Steenblik, R. (2012). *Green Growth and the Futurn of Aviation*. Paper presented at the 27th Round Table on Sustainable Development, OECD Headquarters, Paris, France. https://www.oecd.org/sd-roundtable/papersandpublications/49482790.pdf

Brueckner, J. K., & Zhang, A. (2010). Airline emission charges: Effects on airfares, service quality, and aircraft design. *Transportation Research Part B: Methodological, 44*(8–9), 960-971. doi: http://dx.doi.org/10.1016/j.trb.2010.02.006

Bureau of Infrastructure Transport and Regional Economics (BITRE). (2014). International Airline Activity - Monthly Publications. 2014, from http://www.bitre.gov.au/publications/ongoing/international_airline_activity-monthly_publications.aspx

Bureau of Infrastructure Transport and Regional Economics (BITRE). (2017). Australia's Air Services Agreements/Arrangements. from https://infrastructure.gov.au/aviation/international/agreements.aspx

Burniaux, J.-M., Chateau, J., Dellink, R., Duval, R., Jamet, S., & Alain de Serres (Producer). (2009). The Economics of Climate Change Mitigation Policies and Options for Global Action Beyond 2012. Retrieved from http://www.oecd.org/env/cc/theeconomicsofclimatechangemitigationpoliciesandoptionsforglobalactionbeyond2012.htm

Button, K., & McDougall, G. (2006). Institutional and structure changes in air navigation service-providing organizations. *Journal of Air Transport Management, 12*(5), 236-252. doi: http://dx.doi.org/10.1016/j.jairtraman.2006.07.001

CAPA - Centre for Aviation. (2013). Airbus A330 continues to pull in sales even as the 787 Dreamliner recovers momentum. http://centreforaviation.com/analysis/airbus-a330-continues-to-pull-in-sales-even-as-the-787-dreamliner-recovers-momentum-111317

CAPA - Centre for Aviation. (2016). China-Australia aviation: one million visitors & flights on 21 city-pairs from 12 Chinese cities. from http://centreforaviation.com/analysis/china-australia-aviation-one-million-visitors-flights-on-21-city-pairs-from-12-chinese-cities-261773

Carbon Footprint. (2014). Flight carbon footprint calculator. Retrieved 29 Sept, 2014, from http://calculator.carbonfootprint.com/calculator.aspx?tab=3

Carbon Neutral. (2014). Air Travel Carbon Calculator. Retrieved 30 Sept, 2014, from http://www.carbonneutral.com.au/carbon-calculator/air-travel.html

Cathay Pacific. (2012). Annual Report. from https://www.cathaypacific.com/content/dam/cx/about-us/investor-relations/interim-annual-reports/en/2012_annual-report_en.pdf

Cebreiro-Gómez, A., Heady, C., Vassnes, E., Ashiabor, H., Barde, J.-P., Braathen, N. A., & Scapecchi, P. (2006). *The Political Economy of Environmentally Related Taxes* (pp. 203). Retrieved from http://www.oecd.org/env/tools-evaluation/thepoliticaleconomyofenvironmentallyrelatedtaxes.htm

Cherry, T. L., García, J. H., Kallbekken, S., & Torvanger, A. (2014). The development and deployment of low-carbon energy technologies: The role of economic interests and cultural worldviews on public support. *Energy Policy*(0), 1-5. doi: http://dx.doi.org/10.1016/j.enpol.2014.01.018

Choi, A. S., & Ritchie, B. W. (2014). Willingness to pay for flying carbon neutral in Australia: an exploratory study of offsetter profiles. *Journal of Sustainable Tourism, 22*(8), 1236-1256. doi: 10.1080/09669582.2014.894518

Chong, J. (2014). Air New Zealand farewells the 747. *Australian Aviation*. http://australianaviation.com.au/2014/09/air-new-zealand-farewells-the-747/

Clark, P. (2010). *Stormy Skies: Airlines in Crisis*. Burlington, VT: Ashgate.

Commonwealth of Australia. (2012). Managing the Carbon Footprint of Australian Aviation. http://www.icao.int/environmental-protection/Lists/ActionPlan/Attachments/1/Australia_en.pdf

Commonwealth Scientific and Industrial Research Organisation (CSIRO). (2011). *Flight path Sustainable Aviation.* . Canberra: CSIRO Retrieved from https://publications.csiro.au/rpr/pub?list=BRO&pid=csiro:EP107203&sb=RECENT&n=1&rpp=25&page=294&tr=189421&dr=all

https://publications.csiro.au/rpr/download?pid=csiro:EP107203&dsid=DS3.

Davies, Z. G., & Armsworth, P. R. (2010). Making an impact: The influence of policies to reduce emissions from aviation on the business travel patterns of individual corporations. *Energy Policy, 38*(12), 7634-7638. doi: http://dx.doi.org/10.1016/j.enpol.2010.09.007

Delta Air Lines. (2012). Annual Report. from http://www.delta.com/content/dam/delta-www/pdfs/about-financial/DeltaAirLines_10K_2012.pdf

Deonandan, I., & Balakrishnan, H. (2010). *Evaluation of Strategies for Reducing Taxi-out Emissions at Airports*. Paper presented at the 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, Texas. http://www.mit.edu/~hamsa/pubs/DeonandanBalakrishnanATIO2010.pdf

deSerres, A., Llewellyn, J., & Llewellyn, P. (2011). *The Political Economy of Climate Change Mitigation Policies: How to Build a Constituency to Address Global Warming? OECD Economics Department Working Papers No. 887* Retrieved from http://www.oecd-ilibrary.org/docserver/download/5kg5d5nhcnkb-en.pdf?expires=1481668808&id=id&accname=guest&checksum=F99DDFEE440B1E49988A33CB48389BF4 doi:10.1787/5kg5d5nhcnkb-en

Dillingham, G. L., Merritt, Z. D., Aussendorf, P., Wasleski, M. K., Colwell, W., Dickerson, L., . . . Wood, E. (2014). Alternative Jet Fuels. 441 G St. N.W.

Washington, DC 20548: US Government Accountability Office.

Dixon, M. C. (2006). The maintenance costs of aging aircraft : insights from commercial aviation. from http://www.rand.org/content/dam/rand/pubs/monographs/2006/RAND_MG486.pdf

Dray, L. (2013). An analysis of the impact of aircraft lifecycles on aviation emissions mitigation policies. *Journal of Air Transport Management, 28*, 62-69. doi: 10.1016/j.jairtraman.2012.12.012

Dray, L. M., Evans, A., Reynolds, T. G., Schäfer, A., & Vera-Morales, M. (2009). *Opportunities for Reducing Aviation-Related GHG Emissions: A Systems Analysis for Europe* Retrieved from http://www.verifavia.com/bases/ressource_pdf/125/OMEGA-Reducing-Aviation-GHG.pdf

Duval, R. (2008). A Taxonomy of Instruments to Reduce Greenhouse Gas Emissions and their Interaction. http://www.oecd-ilibrary.org/docserver/download/236846121450.pdf?expires=1481669115&id=id&accname=guest&checksum=A2FDE48F3526A78427F49AA51CB59F9A doi:10.1787/236846121450

Eden, P. (2013). Less is more. *Aircraft Cabin Management, 2*. http://www.aircraftcabinmanagement.com/feature/weight-reduction-in-airline-seats?session_id=omd4ajn3cgsrqa6k5u2uf9c9e7

Emirates. (2012). Annual Report. from http://www.theemiratesgroup.com/english/facts-figures/archive/2011-2012.aspx

Etihad. (2012). Annual Report. from http://www.etihad.com/Documents/PDFs/Corporate%20profile/Corporate%20reports%20and%20CSR/annual-2012-en.pdf

European Environment Agency (Producer). (2006). EMEP/CORINAIR Emission Inventory Guildbook - 2006/ Group 8: Other mobile sources and machinery (B851 Annex). Retrieved from http://www.eea.europa.eu/publications/EMEPCORINAIR3/page017.html, www.eea.europa.eu/publications/EMEPCORINAIR3/B851vs2.4.pdf, http://www.eea.europa.eu/publications/technical_report_2001_3/B851vs2.3spreadsheet1.pdf

European Union Court of Justice. (2011). European Court Justice Press Release No 139/11. http://europa.eu/rapid/press-release_CJE-11-139_en.htm?locale=en

Export-import Bank of the United States. (2012). The Aviation Exports policy. Retrieved 17 Feb, 2014, from http://www.exim.gov/generalbankpolicies/aviation-exports.cfm

Export-import Bank of the United States. (2016). About CIRR. from http://www.exim.gov/tools-for-exporters/commercial-interest-reference-rates/about-cirr-rates

Farries, P., & Eyers, C. (2008). *Aviation CO2 Emissions Abatement Potential from Technology Innovation Building a low-carbon economy-the UK's contribution to tackling climate change* Retrieved from https://www.theccc.org.uk/archive/aws2/Aviation%20Report%2009/QinetiQ_aviation_report_for_the_CCC.pdf

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management, 55*(2), 142-162. doi: 10.1016/j.jeem.2007.11.001

Flightglobal. (2009). Picture: First Air New Zealand 767-300ER with new blended winglets. *Flightglobal*. http://www.flightglobal.com/news/articles/picture-first-air-new-zealand-767-300er-with-new-blended-329612/

Flottau, J., Broderick, S., Unnikrishnan, M., & Schofield, A. (2015). Drop In Oil Prices Means An Airline Profitability Boost Now, But... *Aviation Week & Space Technology*. from http://aviationweek.com/commercial-aviation/drop-oil-prices-means-airline-profitability-boost-now

Flynn, D. (2013). United to operate 777s on Australia routes. *Australian Business Traveller*. http://www.ausbt.com.au/united-upgrades-sydney-flights-to-boeing-777s

Flynn, D. (2015a). Emirates to replace entire Boeing 777 fleet with 777X jets. *Australian Business Traveller*. http://www.ausbt.com.au/emirates-to-replace-boeing-777-fleet-with-777-8x-777-9x-jets

Flynn, D. (2015b). Virgin Australia boosts Boeing 737 MAX order, via delayed 737s. *Australian Business Traveller*. http://www.ausbt.com.au/virgin-australia-boosts-boeing-737-max-order-via-delayed-737s

Forsberg, D. (2015). Aircraft Retirement and Storage Trends. http://avolon.aero/wp/wp-content/uploads/2015/03/Avolon-White-Paper-FInal-30-March-2015.pdf

Forsberg, D., & Mollan, L. (2013). Transitioning to Neo and Max: An Investor's Guide. http://avolon.aero/wp/wp-content/uploads/2014/05/Avolon_Transition_Paper_Final.pdf

Frawley, G. (2014a). End of an era as Qantas farewells the 767. *Australian Aviation*. http://australianaviation.com.au/2014/12/end-of-an-era-as-qantas-farewells-the-767/

Frawley, G. (2014b). Qantas to consider new narrowbody options in the “medium term”. *Australian Aviation*. http://australianaviation.com.au/2014/11/qantas-to-consider-new-narrowbody-options-in-the-medium-term/

Freed, J. (2016). How the airline industry is managing the 'good oil'. *The Sydney Morning Herald*. from http://www.smh.com.au/business/aviation/how-the-airline-industry-is-managing-the-good-oil-20160224-gn2em2.html

Gans, J. S. (2012). Innovation and Climate Change Policy. *American Economic Journal: Economic Policy, 4*(4), 125-145. doi: 10.1257/pol.4.4.125

Garretson, C. (2010). Pulling the plug on old hardware: Life-cycle management explained. *ComputerWorld*. from http://www.computerworld.com/article/2517337/computer-hardware/pulling-the-plug-on-old-hardware--life-cycle-management-explained.html?page=2

Garuda. (2012). Annual Report. from https://www.garuda-indonesia.com/files/pdf/AR-GA-2012.pdf

Gegg, P., Budd, L., & Ison, S. (2014). The market development of aviation biofuel: Drivers and constraints. *Journal of Air Transport Management, 39*, 34-40. doi: 10.1016/j.jairtraman.2014.03.003

Gegg, P., Budd, L., & Ison, S. (2015). Stakeholder Views of the Factors Affecting theCommercialization of Aviation Biofuels in Europe. *International Journal of Sustainable Transportation, 9*(8), 542-550.

Gillen, D. (2011). The evolution of airport ownership and governance. *Journal of Air Transport Management, 17*(1), 3-13. doi: 10.1016/j.jairtraman.2010.10.003

Goulder, L. H., & Parry, I. W. H. (2008). Instrument Choice in Environmental Policy. *Review of Environmental Economics and Policy, 2*(2), 152-174. doi: 10.1093/reep/ren005

Graham, W. R., Hall, C. A., & Vera Morales, M. (2014). The potential of future aircraft technology for noise and pollutant emissions reduction. *Transport Policy, 34*, 36-51. doi: http://dx.doi.org/10.1016/j.tranpol.2014.02.017

Green, J., Leitch, S.-A., Beesley, C., Bickerstaff, C., Collins, P., Eyers, C., . . . Wrede, R. v. (2005). *Air Travel – Greener by Design*. In R. A. Society (Series Ed.) *Mitigating the Environmental Impact of Aviation: Opportunities and Priorities* Retrieved from https://www.aerosociety.com/Assets/Docs/About_Us/Greener%20By%20Design/GbD%20-%202005%20Science%20and%20Technology%20Report.pdf

Grewe, V., Champougny, T., Matthes, S., Frömming, C., Brinkop, S., Søvde, O. A., . . . Halscheidt, L. (2014). Reduction of the air traffic's contribution to climate change: A REACT4C case study. *Atmospheric Environment, 94*, 616-625. doi: http://dx.doi.org/10.1016/j.atmosenv.2014.05.059

Griffiths, E. (2014). Qantas forcing Government to consider assistance, Treasurer Joe Hockey says. http://www.abc.net.au/news/2014-02-13/qantas-forcing-government-to-consider-funding-joe-hockey-says/5258446

Groenenboom, J., Bruinsma, R., Beechcroft-Kay, M., Markou, C., Cros, G., Margeirsson, E., & Pascalis, T. (2016). *Guidance Material and Best Practices for Aircraft Leases* Retrieved from https://www.iata.org/whatwedo/workgroups/Documents/ALAG/AC-leases-2nd-edition.pdf

Gubisch, M. (2010). New Lufthansa seat saves nearly 30% in weight. *Flightglobal*. https://www.flightglobal.com/news/articles/new-lufthansa-seat-saves-nearly-30-in-weight-350995/

Gubisch, M. (2013). Boeing plans first B777X flight in 2019. *Flightglobal*. https://www.flightglobal.com/news/articles/dubai-boeing-plans-first-777x-flight-in-2019-393206/

Hamamoto, M. (2013). Energy-saving behavior and marginal abatement cost for household CO2 emissions. *Energy Policy*(0), 1-5. doi: http://dx.doi.org/10.1016/j.enpol.2013.08.082

Hammar, H., Lofgren, A., & Sterner, T. (2004). Political Economy Obstacles to Fuel Taxation. *The Energy Journal*, *25*(3), 1-17.

Hawaiian Airlines. (2012). Annual Report. from https://newsroom.hawaiianairlines.com/internal_redirect/cms.ipressroom.com.s3.amazonaws.com/249/files/20156/Hawaiian%20Holdings%2010-K%20Annual%20Report.pdf

Hileman, J. I., De la Rosa Blanco, E., Bonnefoy, P. A., & Carter, N. A. (2013). The carbon dioxide challenge facing aviation. *Progress in Aerospace Sciences*, *63*, 84-95. doi: http://dx.doi.org/10.1016/j.paerosci.2013.07.003

Hofer, C., Dresner, M. E., & Windle, R. J. (2010). The environmental effects of airline carbon emissions taxation in the US. *Transportation Research Part D: Transport and Environment*, *15*(1), 37-45. doi: https://doi.org/10.1016/j.trd.2009.07.001

Holland, M., Mann, M., Ralph, M., Owen, B., Lee, D., Horton, G., . . . Kollamthodi, S. (2011). A Marginal Abatement Cost Curve Model for the UK Aviation Sector. http://www.icao.int/environmental-protection/Documents/ActionPlan/UK_AbatementModel_en.pdf

Horton, G. (2010). *Future Aircraft Fuel Efficiencies - Final Report* (pp. 1-97). Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4515/future-aircraft-fuel-efficiency.pdf

Hughes, N. (2013). Apple's iPad now in use in all American Airlines cockpits. Retrieved 23-April, 2015, from http://appleinsider.com/articles/13/06/24/apples-ipad-now-in-use-in-all-american-airlines-cockpits

http://hub.aa.com/en/nr/pressrelease/american-airlines-completes-electronic-flight-bag-implementation

Huppes, G., & Simonis, U. E. (2009). Environmental Policy Instruments. In J. Boersema & L. Reijnders (Eds.), Principles of Environmental Sciences (pp. 239-280): Springer Netherlands. Retrieved from http://dx.doi.org/10.1007/978-1-4020-9158-2_13. doi: 10.1007/978-1-4020-9158-2_13

ICAO. (2008). *Guidance on the Use of Emissions Trading for Aviation* Retrieved from http://www.icao.int/environmental-protection/Pages/EmissionsTrading.aspx

ICAO. (2009). Civil Aviation Statistics - Available Capacity and Average Passenger Mass. http://www.icao.int/Meetings/STA10/Documents/Sta10_Wp005_en.pdf

ICAO. (2010). Environmental Report Aviation Outlook. http://www.icao.int/environmental-protection/Documents/EnvironmentReport-2010/ICAO_EnvReport10-Outlook_en.pdf

ICAO. (2013a). Assembly—38th Session Report of the Executive Commitee on Agenda Item 17 (Section on Climate Change). http://www.icao.int/Meetings/a38/Documents/WP/wp430_en.pdf

ICAO. (2013b). Glossary v1 2. www.icao.int/dataplus_archive/Documents/GLOSSARY.docx

ICAO. (2013c). Resolutions adopted by the Assembly. from http://www.icao.int/Meetings/a38/Documents/Resolutions/a38_res_prov_en.pdf

ICAO. (2014a). Carbon Emissions Calculator. Retrieved 29 Sept, 2014, from http://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx

ICAO. (2014b). Methodology ICAO Carbon Calculator V7. http://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v7-2014.pdf

ICAO. (2015). ICAO Welcomes COP21 Agreement, Will Continue to Provide Leadership and Coordinate Action on International Aviation's Environmental Goals. from http://www.icao.int/Newsroom/Pages/ICAO-Welcomes-COP21-Agreement.aspx

ICAO. (2016a). Environmental Protection-Global Market-Based Measure Scheme. from http://www.icao.int/Meetings/a39/workshops/Documents/A39%20Workshop%20-%20GMBM.pdf

ICAO. (2016b). ICAO Environmental Report. from http://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf

ICAO. (2016c). ICAO High-level Meeting on a Global Market-Based Measure (MBM) Scheme. from http://www.icao.int/Meetings/HLM-MBM/Pages/HLM_briefing.aspx

http://www.icao.int/Meetings/HLM-MBM/Documents/20160504_HLM_Pre-Event_Overview%20of%20ICAOs%20Work%20on%20GMBM_V04.pdf

http://www.icao.int/Meetings/HLM-MBM/Documents/20160504_HLM_Pre-Event_Draft%20AR%20text_V05.pdf

http://www.icao.int/Meetings/HLM-MBM/Documents/20160504_HLM_Pre-Event_Role%20of%20Carbon%20Markets%20in%20ICAO%20global%20MBM_V04.pdf

ICAO. (2016d). Resolution A39-3: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme from http://www.icao.int/environmental-protection/Documents/Resolution_A39_3.pdf

ICAO. (2017). International Civil Aviation Organization. from http://www.icao.int/about-icao/Pages/default.aspx

ICAO CAEP. (2016). ICAO Environment Advisory Group Meeting (EAG/15). from http://www.icao.int/Meetings/HLM-MBM/Documents/EAG15_CAEP%20Technical%20Analyses.pdf

http://www.icao.int/Meetings/HLM-MBM/Documents/EAG15_CAEP%20Technical%20Analyses_Appendix.pdf

ifenews. (2012). Emirates Showcase New In-Flight Entertainment System. from https://ifenews.wordpress.com/2012/07/02/emirates-showcase-new-in-flight-entertainment-system-3/

Innovata. (2014). Flight Schedules Database. 2014, from http://www.innovata-llc.com/data/flight-schedules-database/

International Air Transport Association (IATA). (2009). A Global Approach to Reducing Aviation Emissions. 1-8. http://corporate.airfrance.com/fileadmin/dossiers/img_rte_fr/IATA.pdf

International Air Transport Association (IATA). (2013a). Annual General Meeting (AGM) Resolution - Carbon Neutral Growth. *IATA AGM*. https://www.iata.org/pressroom/pr/Documents/agm69-resolution-cng2020.pdf

International Air Transport Association (IATA). (2013b). New Year's Day 2014 marks 100 Years of Commercial Aviation from http://www.iata.org/pressroom/pr/Pages/2013-12-30-01.aspx

International Air Transport Association (IATA). (2016). Fact Sheet - Fuel. from https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf

International Air Transport Association (IATA), Georgia Tech, & German Aerospace Center (DLR). (2013). *IATA Technology Roadmap*. In IATA (Series Ed.) Retrieved from https://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2013.pdf

International Airlines Group Legal Department. (2011). Response of the IAG group to EC's request for consultation on a review of short-term export credit insurance. http://ec.europa.eu/competition/consultations/2011_export_credit/iag_en.pdf

IPCC. (1999). *IPCC Special Report Aviation and the Global Atmosphere Summary for Policymakers* (pp. 1-23). Retrieved from https://www.ipcc.ch/pdf/special-reports/spm/av-en.pdf

IPCC. (2007). *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Retrieved from http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html

Jardine, C. N. (2009). Calculating The Carbon Dioxide Emissions Of Flights. 1-20. http://www.eci.ox.ac.uk/research/energy/downloads/jardine09-carboninflights.pdf

Jet Fuel Intelligence. (2009). Benefits Of Engine Washing Climb Along With Fuel Costs. *Jet Fuel Intelligence*. http://search.proquest.com/docview/199408948?accountid=14723

http://cf5pm8sz2l.search.serialssolutions.com/?&genre=article&sid=ProQ:&atitle=Benefits+Of+Engine+Washing+Climb+Along+With+Fuel+Costs&title=Jet+Fuel+Intelligence&issn=15281183&date=2009-07-06&volume=&issue=&spage=&author=Anonymous

Kaminski-morrow, D. (2010). Austrian to refit 32 A320s and 737s with new seats. *Flight Global*. https://www.flightglobal.com/news/articles/austrian-to-refit-32-a320s-and-737s-with-new-seats-350030/

Kar, R., Bennefoy, P. A., & Hansman, R. J. (2010). *Dynamics of Implementation of Mitigating Measures to Reduce CO2 Emissions from Commercial Aviation* Retrieved from https://dspace.mit.edu/bitstream/handle/1721.1/56268/Kar_et_al_ICAT_Report.pdf

Kirby, M. (2014). Spirit Airlines taps Acro for 5,000 slim seats. Retrieved 23-April, 2015, from http://www.runwaygirlnetwork.com/2014/01/10/spirit-airlines-taps-acro-5000-slim-seats/

Kirchgassner, G., & Schneider, F. (2003). On the Political Economy of Environmental Policy. *Public Choice*, *115*, 369-396.

Kling, M., & Hough, I. (2010). *Carbon Modeling Methodology* (pp. 1-41). Retrieved from http://numbers.brighterplanet.com/2010/06/29/emissions-modeling-methodology-published/

Kling, M., & Hough, I. (2011). Air Travel Carbon and Energy Efficiency. 1-25. http://www.climateaccess.org/sites/default/files/Kling_Air%20Travel%20Carbon%20and%20Energy%20Efficiency.pdf

Knoema. (2015). US Inflation Forecast. Retrieved 24 Nov, 2015, from http://knoema.com/kyaewad/us-inflation-forecast-2015-2020-and-up-to-2060-data-and-charts

Knorr, A., Bellmann, J., & Schomaker, R. (2012). Subsidies in Civil Aircraft Manufacturing: The World Trade Organization (WTO) and the Boeing Airbus Dispute. *European State Aid Law Quarterly : EStAL, 11*(3), 585-599.

Kohler, A. (2001). Air New Zealand to be re-nationalised. http://www.abc.net.au/7.30/content/2001/s382720.htm

Kovacs, K. F., Haight, R. G., Jung, S., Locke, D. H., & O'Neil-Dunne, J. (2013). The marginal cost of carbon abatement from planting street trees in New York City. *Ecological Economics, 95*, 1-10. doi: 10.1016/j.ecolecon.2013.08.012

KPMG. (2007). Components of Aircraft Acquisition Cost, Associated Depreciation and Impairment Testing in the Global Airline Industry. from https://www.kpmg.com/Global/en/IssuesAndInsights/ArticlesPublications/Documents/components-of-aircraft-acquisition.pdf

Kuhn, M. (2009). PICTURES: Winglet installation underway for Hawaiian 767s. *Flightglobal*. http://www.flightglobal.com/news/articles/pictures-winglet-installation-underway-for-hawaiian-334475/

Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., . . . Sausen, R. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment, 43*(22-23), 3520-3537. doi: 10.1016/j.atmosenv.2009.04.024

Lee, J., & Mo, J. (2011). Analysis of Technological Innovation and Environmental Performance Improvement in Aviation Sector. *International Journal of Environmental Research and Public Health*, 3777-3795. doi: 10.3390/ijerph8093777

Li, Y., Wang, Y.-z., & Cui, Q. (2016). Has airline efficiency affected by the inclusion of aviation into European Union Emission Trading Scheme? Evidences from 22 airlines during 2008–2012. *Energy, 96*, 8-22. doi: https://doi.org/10.1016/j.energy.2015.12.039

Liu, j., Moss, S., & Zhang, J. (2011). The Life Cycle of a Pandemic Crisis: SARS Impact on Air Travel. *Journal of International Business Research*, 63-78.

Lovegren, J. A., & Hansman, R. J. (2011). Estimation of Potential Aircraft Fuel Burn reduction in Cruise via Speed and Altitude Optimization Strategy: Massachusetts Institute of Technology.

Lu, J.-L., & Shon, Z. Y. (2012). Exploring airline passengers' willingness to pay for carbon offsets. *Transportation Research Part D: Transport and Environment, 17*(2), 124-128. doi: https://doi.org/10.1016/j.trd.2011.10.002

Lufthansa Systems. (2012). BoardConnect: Run the future, not cables. Revolutionizing in-flight entertainment. from https://www.lhsystems.com/solutions-services/airline-solutions-services/inflight-entertainment/boardconnect.html

Lufthansa Technik. (2015). Cyclean Engine Wash. Retrieved 24/9/2015, from http://www.lufthansa-technik.com/cyclean

Lufthansa Technik. (2016). Aircraft Maintenance. Retrieved 24/Jun/2016, 2016, from http://www.lufthansa-technik.com/aircraft-maintenance

Lyon, T. P., & Maxwell, J. W. (2003). Self-regulation, taxation and public voluntary environmental agreements. *Journal of Public Economics, 87*(7–8), 1453-1486. doi: http://dx.doi.org/10.1016/S0047-2727(01)00221-3

Malaysia Airlines. (2012). Annual Report. from http://ir.chartnexus.com/mas/website_HTML/attachments/attachment_32862_1366604341.pdf

Mangla, I. (2015). Germanwings 9525: How Does An Airline Decide A Plane Is Too Old To Fly? *International Business Times*. http://www.ibtimes.com/germanwings-9525-how-does-airline-decide-plane-too-old-fly-1857746

Marbaix, P., Ferrone, A., & Matthews, B. (2008). Inclusion of Non CO2 effects of Aviation in the ETS. 1-11. http://dev.ulb.ac.be/ceese/ABC_Impacts/documents_abc/Note_to_stakeholders_aviation_nonco2.pdf

Markou, C., & Cros, G. (2013). Airline Maintenance Cost Executive Commentary (FY2012). Montreal, Canada: IATA.

Maxon, T. (2012). Southwest Airlines revamps and adds seats. Retrieved 22-April, 2015, from http://www.dallasnews.com/business/airline-industry/20120117-southwest-airlines-adds-seats-to-expand-capacity-without-adding-airplanes.ece

http://aviationblog.dallasnews.com/2012/01/southwest-airlines-to-revamp-i.html/

McConnachie, D. A. T. (2012). *Climate Policy and the Airline Industry: Emissions Trading and Renewable Jet Fuel* Vol. MSc. *Engineering Systems Division* Retrieved from https://dspace.mit.edu/handle/1721.1/72902

Mckenna, E. (2013). Product Focus: Electronic Flight Bags. *Avionics Today*. from http://www.aviationtoday.com/av/issue/cover/Product-Focus-Electronic-Flight-Bags_80135.html#.VThcyZPqVKh

Michaels, D. (2012). The Secret Price of a Jet Airliner. *The Wall Street Journal*. from http://www.wsj.com/articles/SB10001424052702303649504577494862829051078

Miyoshi, C., & Mason, K. J. (2009). The carbon emissions of selected airlines and aircraft types in three geographic markets. *Journal of Air Transport Management, 15*(3), 138-147. doi: 10.1016/j.jairtraman.2008.11.009

Miyoshi, C., & Merkert, R. (2015). The Economic and CO2 Emissions Performance in Aviation: An Empirical Analysis of Major European Airlines. In B. Fahimnia, M. G. H. Bell, D. A. Hensher & J. Sarkis (Eds.), Green Logistics and Transportation A Sustainable Supply Chain Perspective (pp. 175-190): Springer Verlag.

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., . . . Moxey, A. (2011). Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. *Journal of Agricultural Economics, 62*(1), 93-118. doi: 10.1111/j.1477-9552.2010.00268.x

Morrell, P. (2009). The potential for European aviation CO2 emissions reduction through the use of larger jet aircraft. *Journal of Air Transport Management, 15*(4), 151-157. doi: 10.1016/j.jairtraman.2008.09.021

Morrell, P., & Dray, L. (2009). Environmental aspects of fleet turnover, retirement and life cycle (Final Report). http://www.obsa.org/Lists/Documentacion/Attachments/274/Environmental_aspects_fleet_turnover_retirement_life_cycle_EN.pdf

Morris, J., Rowbotham, A., Angus, A., Mann, M., & Pol, I. (2009). A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector. OMEGA Project 14 - Draft Final Report. http://www.cate.mmu.ac.uk/wp-content/uploads/2012/06/Framework-for-marginal-costs-of-abatement.pdf

http://www.cate.mmu.ac.uk/wp-content/uploads/2012/06/omega-14-final-draft-v2-020309.pdf

Morris, J., Rowbotham, A., Morrell, P., Foster, A., Poll, I., Owen, B., . . . Ralph, M. (2009). UK Aviation: Carbon Reduction Futures.

https://dspace.lib.cranfield.ac.uk/bitstream/1826/3577/1/UK_Aviation_Carbon_Reduction_Futures-2009.pdf

Morrison, S. A., & Winston, C. (1989). Airline Deregulation and Public Policy. *Science, 245*(4919), 707.

myClimate. (2014). Offset your flight emissions. Retrieved 30 Sept, 2014, from https://co2.myclimate.org/en/flight_calculators/new

National Research Council, Transport Research Board, Airport Cooperative Research Program, Administration, U. S. F. A., Camp Dresser & McKee, & Synergy Consulting Services. (2011). Handbook for considering practical greenhouse gas emission reduction strategies for airports. Washington D.C.

Norris, G. (2013). Boeing Launches 777X In Dubai Order Boom. *Aviation Week*. http://aviationweek.com/commercial-aviation/boeing-launches-777x-dubai-order-boom

Oates, W. E., & Portney, P. R. (2003). The political economy of environmental policyHandbook of Environmental Economics (pp. 325-354).

OECD. (2007). Instrument Mixes for Environmental Policy *Analysis of Current Use of Instrument Policy* (pp. 238). paris: OECD Publishing.

OECD (Producer). (2016). Historical Commercial Interest Reference Rate (CIRR) Retrieved from http://www.oecd.org/tad/xcred/xls-historical_1993_today.xlsx

Official Airline Guide (OAG). (2014). Aviation data. from http://www.oag.com/Aviation-Data

Owen, B., Lee, D. S., & Lim, L. (2010). Flying into the Future: Aviation Emissions Scenarios to 2050. *Environ Sci Technol, 44*(7), 2255-2260.

Owen, D. (2014). Game of Thrones: How airlines woo the one per cent. *The New Yorker*. from http://www.newyorker.com/magazine/2014/04/21/game-of-thrones

Pagoni, I., & Psaraki-Kalouptsidi, V. (2016). The impact of carbon emission fees on passenger demand and air fares: A game theoretic approach. *Journal of Air Transport Management, 55*, 41-51. doi: 10.1016/j.jairtraman.2016.04.004

Pearce, B. (2013). *Profitability and the air transport value chain* Retrieved from https://www.iata.org/whatwedo/Documents/economics/profitability-and-the-air-transport-value%20chain.pdf

Pearce, D. (2005). *Th UK Climate Change Levy: A Study in Political Economy* Retrieved from http://www.oecd-ilibrary.org/docserver/download/0205051ec003.pdf?expires=1481674708&id=id&accname=ocid177546&checksum=2FCD630DE5226C9355447381869A3D3B

Poll, D. I. A. (2014). On the application of light weight materials to improve aircraft fuel burn - reduce weight or improve aerodynamic efficiency? *Aeronautical Journal, 118*(1206), 903-934.

Pratt & Whitney. (2010). Jetstar Airways Selects Pratt & Whitney EcoPower® Engine Wash. *AviTrader*. http://www.pw.utc.com/Press/Story/20101103-0100/2010/All%20Categories

http://www.avitrader.com/2010/11/03/jetstar-airways-selects-pratt-whitney-ecopower-engine-wash/

Qantas. (2010). The Qantas Group at a Glance. from https://www.qantas.com.au/infodetail/about/FactFiles.pdf

Qantas (Producer). (2011). Energy Efficiency Opportunities. Retrieved from https://www.qantas.com.au/infodetail/about/investors/qantasEEOReport2011.pdf

Qantas. (2012a). Annual Report. from https://www.qantas.com.au/infodetail/about/investors/2012AnnualReport.pdf

Qantas (Producer). (2012b). Energy Efficiency Opportunities. Retrieved from https://www.qantas.com.au/infodetail/about/investors/qantasEEOReport2012.pdf

Qantas. (2013a). Annual Report. from https://www.qantas.com.au/infodetail/about/investors/2013AnnualReport.pdf

Qantas (Producer). (2013b). Energy Efficiency Opportunities. Retrieved from https://www.qantas.com.au/infodetail/about/investors/qantasEEOReport2013.pdf

Qantas. (2014). Offset My Flight. Retrieved 29 Sept, 2014, from https://www.qantas.com.au/travel/airlines/offset-my-flight/global/en

Qantas. (2015). QANTAS Dreamliners Symbolise new era for National Carrier. . Retrieved 24/9/2015, from http://www.qantasnewsroom.com.au/media-releases/qantas-dreamliners-symbolise-new-era-for-national-carrier/

http://www.ausbt.com.au/qantas-to-buy-boeing-787-first-flights-from-2017

http://australianaviation.com.au/2015/08/joyce-says-787-9-represents-hugely-exciting-opportunities-for-qantas/

Qiu, Y. (2005). Can the 787 & A350 transform the economics of long-haul services? *Aircraft Commerce*, (39). http://www.aircraft-commerce.com/sample_articles/sample_articles/fleet_planning_sample.pdf

Ramos-Pérez, D. (2016). State aid to airlines in Spain: An assessment of regional and local government support from 1996 to 2014. *Transport Policy*, *49*, 137-147. doi: http://dx.doi.org/10.1016/j.tranpol.2016.05.004

Ramsey, J. (2011). In-Flight Entertainment. *Avionics*. http://www.aviationtoday.com/av/communications/In-Flight-Entertainment_74212.html#.VX-G70bqVKg

Reuters. (2012). How can an airline pay $20 billion for new planes? . http://www.traveller.com.au/how-can-an-airline-pay-20-billion-for-new-planes-1tnbg

Reyd, J. V. d., & Wouters, M. (2005). Air Cargo Density Research. http://www.pdfdrive.net/air-cargo-density-final-e4257838.html

Ribeiro, S. K., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., D. S. Lee, . . . Zhou, P. J. (2007). Transport and its infrastructure. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 323-386). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch5.html.

Roewe, K. (2014). A320neo Unbeatable fuel efficiency. http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/a320neo-family-sets-new-standards-with-20-reduced-fuel-burn/

Rothman, A. (2014). Airbus Seeks 15,000 A320neo Sales in 20 Years to Lower Fuel. *BloombergBusiness*. http://www.bloomberg.com/news/articles/2014-09-25/airbus-seeks-15-000-a320neo-sales-in-20-years-to-drive-savings

Schonland, A. (2016). Aircraft pricing - List vs. Market. Retrieved 5-May-2016, 2016, from http://airinsight.com/2016/05/16/aircraft-pricing-list-vs-market/

Sijm, J. (2005). The interaction between the EU emissions trading scheme and national energy policies. *Climate Policy*, *5*(1), 79-96. doi: 10.1080/14693062.2005.9685542

Singapore Airlines. (2012). Annual Report. from https://www.singaporeair.com/saar5/pdf/Investor-Relations/Annual-Report/annualreport1112.pdf

Smithsonian National Air and Space Museum. (2007). Deregulation: A Watershed Event. Retrieved 17 feb, 2014, from https://airandspace.si.edu/exhibitions/america-by-air/online/jetage/jetage08.cfm

Smithsonian National Postal Museum. (2004). Airmail Creates an Industry: Postal Act Facts. Retrieved 17 Feb, 2014, from http://www.postalmuseum.si.edu/airmail/airmail/public/airmail_public_postal_long.html

http://www.postalmuseum.si.edu/airmail/airmail/airmail.html

Smyth, A., Christodoulou, G., Dennis, N., Al-Azzawi, M., & Campbell, J. (2012). Is air transport a necessity for social inclusion and economic development? *Journal of Air Transport Management, 22*, 53-59. doi: 10.1016/j.jairtraman.2012.01.009

Smyth, M., & Pearce, B. (Producer). (2006). IATA Economics Briefing No. 5 'Airline Cost Performance'. Retrieved from https://www.iata.org/whatwedo/Documents/economics/airline_cost_performance.pdf

https://www.iata.org/publications/economics/Documents/890200-airline-cost-performanceSummary-report.pdf

https://www.iata.org/whatwedo/Documents/economics/IATA_Economic_Briefing_Airline_Cost_Performance_Update.pdf

Sorrell, S. R., & Sijm, J. (2003). Carbon Trading in the Policy Mix. *Oxford Review of Economic Policy, 19*(3), 420-437.

Søvde, O. A., Matthes, S., Skowron, A., Iachetti, D., Lim, L., Owen, B., . . . Isaksen, I. S. A. (2014). Aircraft emission mitigation by changing route altitude: A multi-model estimate of aircraft NOx emission impact on O3 photochemistry. *Atmospheric Environment, 95*, 468-479. doi: http://dx.doi.org/10.1016/j.atmosenv.2014.06.049

Steven, M., & Merklein, T. (2013). The influence of strategic airline alliances in passenger transportation on carbon intensity. *Journal of Cleaner Production, 56*, 112-120. doi: http://dx.doi.org/10.1016/j.jclepro.2012.03.011

Stratton, R. W., Wong, H., & Hileman, J. I. (2010). *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels Partnership for Air Transportation Noise and Emissions Reduction Project 28* Retrieved from http://web.mit.edu/aeroastro/partner/reports/proj28/partner-proj28-2010-001.pdf

Sustainable Aviation. (2010). Aircraft in the Ground CO2 Reduction Programme. from http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/Aircraft-On-the-Ground-CO2-Reduction-Programme-Best-Practice-Guidance.pdf

Sustainable Aviation. (2012). CO2 Road Map. from http://www.sustainableaviation.co.uk/wp-content/uploads/SA-CO2-Road-Map-full-report-280212.pdf

Teal, M. (2014). New 737 Max: Improved Fuel Efficiency and Performance. *Aero*, 5-12. www.boeing.com/boeingedge/aeromagazine

Thomas, G. (2014). Virgin unveils new “business/first” seat. *Australian Aviation*. from http://australianaviation.com.au/2014/09/virgin-unveils-new-businessfirst-seat/

Timilsina, G. R., & Shrestha, A. (2009). Transport sector CO2 emissions growth in Asia: Underlying factors and policy options. *Energy Policy, 37*(11), 4523-4539. doi: http://dx.doi.org/10.1016/j.enpol.2009.06.009

Timotijevic, D. (2013). Aviation Leasing as part of a Broader Investment Portfolio. from https://www.investec.com.au/content/dam/investec/investec-aus/Misc/Investec_Report_Aviation_Leasing_as_Part_of_a_Broader_Investment_Portfolio.pdf

Townend, S. (2011). NEW AIRCRAFT BUSINESS BOOMING BUT MARKET IS volatile. *InFinance, 125*(2), 54-55.

Travis, D. J., Carleton, A. M., & Lauritsen, R. G. (2004). Regional Variations in US Diurnal Temperature Range for the 11-14 September 2001 Aircraft Groundings. *Journal of Climate, 17*, 1123-1134.

Trejos, N. (2013). Will iPads revolutionize in-flight entertainment? *USA Today*. from http://www.usatoday.com/story/travel/flights/2012/12/20/will-ipads-revolutionize-in-flight-entertainment/1782809/

Trimble, S. (2014). Analysis: After three years in service, how is 787 performing? *Flight Global*. Retrieved 26/July/2015, 2015, from http://www.flightglobal.com/news/articles/analysis-after-three-years-in-service-how-is-787-performing-405814/

U.S. Department of Labor. (2015). CPI Inflation Calculator. Retrieved 19-May, 2015, from http://www.bls.gov/data/inflation_calculator.htm

U.S. Energy Information Administration. (2015a). The Annual Energy Outlook 2015 with projections to 2040. from http://www.eia.gov/forecasts/aeo/pdf/0383%282015%29.pdf

U.S. Energy Information Administration. (2015b). U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB. from http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm

U.S. Federal Aviation Administration (FAA). (2005). Advisory Circular: Aircraft Weight and Balance Control. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC120-27E.pdf

U.S. Federal Aviation Administration (FAA). (2015). Aviation Emissions, Impact & Mitigation: A Primer.

United Airlines. (2012). Annual Report. from http://www.sec.gov/Archives/edgar/data/319687/000119312512073010/d260625d10k.htm

United Nations (UN). (1998). Kyoto Protocol to United Nations Framework Convention on Climate Change (UNFCCC). 1-20. http://unfccc.int/kyoto_protocol/items/2830.php

van Renssen, S. (2012). Saving EU climate policy. *Nature Climate Change, 2*(6), 392-393. doi: 10.1038/nclimate1561

Vasigh, B., Fleming, K., & Tacker, T. (2013). *Introduction to Air Transport Economics: From Theory to Applications -- 2nd ed.* (Second ed.). Burlington, USA: Ashgate Publishing Company.

Virgin Australia (Producer). (2011). Energy Efficiency Opportunities. Retrieved from https://www.virginaustralia.com/cs/groups/internetcontent/@wc/documents/webcontent/~edisp/u_023884.pdf

Virgin Australia. (2012a). Annual Report. from http://www.virginaustralia.com/cs/groups/internetcontent/@wc/documents/webcontent/~edisp/annual-rpt-2012.pdf

Virgin Australia (Producer). (2012b). Energy Efficiency Opportunities. Retrieved from https://www.virginaustralia.com/cs/groups/internetcontent/@wc/documents/webcontent/~edisp/eeo_2012.pdf

Virgin Australia. (2013a). Annual Report. from http://www.virginaustralia.com/cs/groups/internetcontent/@wc/documents/webcontent/~edisp/annual-rpt-2013.pdf

Virgin Australia (Producer). (2013b). Energy Efficiency Opportunities. Retrieved from https://www.virginaustralia.com/cs/groups/internetcontent/@wc/documents/webcontent/~edisp/va_public_report_20140801.pdf

Virgin Australia. (2017). Fly Carbon Neutral. from https://www.virginaustralia.com/au/en/about-us/sustainability/carbon-offset-program/

Wall, R., Norris, G., Anselmo, J. C., & Flottau, J. (2011, 27/7/2011). Sellers' Market. *Aviation Week & Space Technology*. from http://aviationweek.com/site-files/aviationweek.com/files/uploads/2015/05/aw_paris_2011.pdf

Woods, R. (2016a). The Big 20: Top cargo airport rankings. 2016, from http://aircargoworld.com/the-big-20-top-cargo-airport-rankings/3/

Woods, R. (2016b). Freight 50: The top 50 cargo carriers. 2016, from http://aircargoworld.com/freight-50-the-top-50-cargo-carriers/

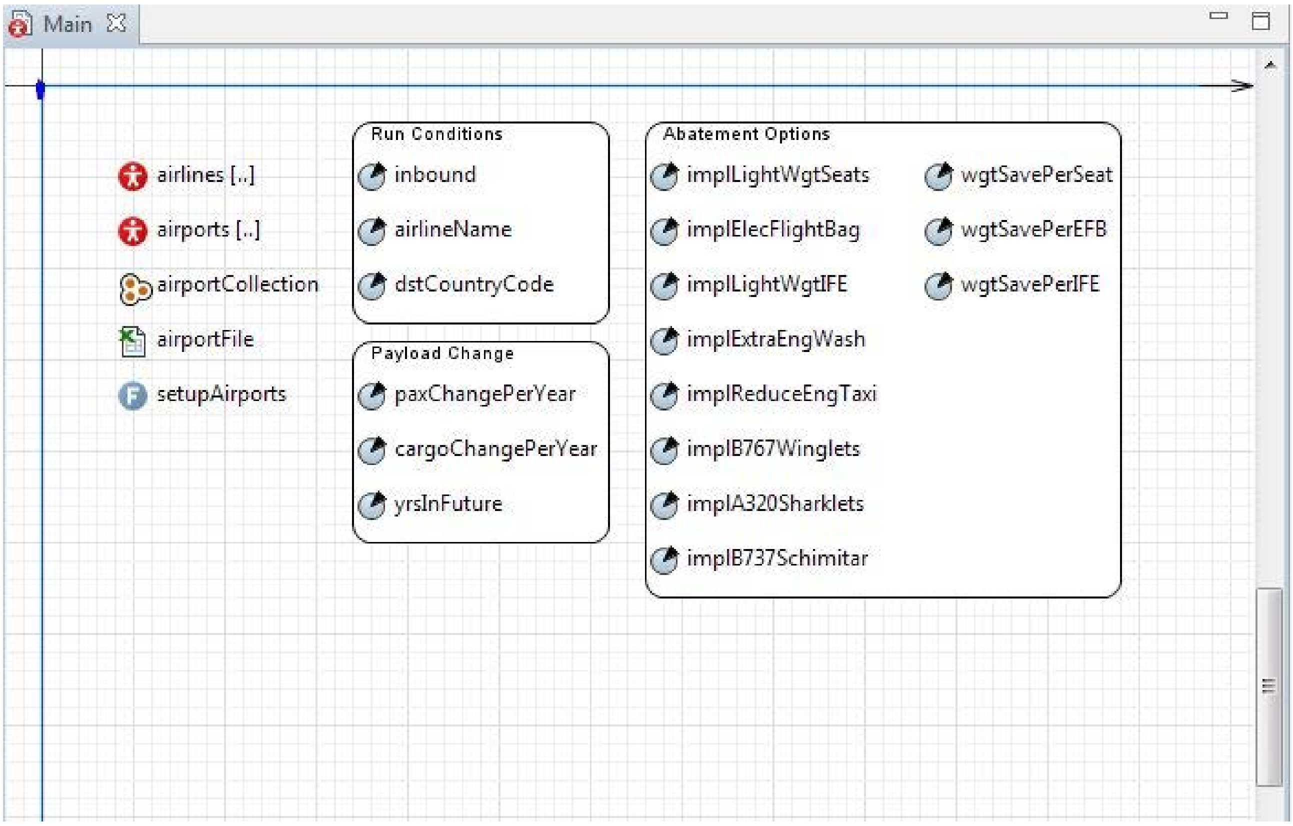
Wren, C. (2011). Less is More. *GreenSky - Aviation and the Environment*. http://www.amsafe.com/wp-content/uploads/GS_October11_AmSafe.pdf

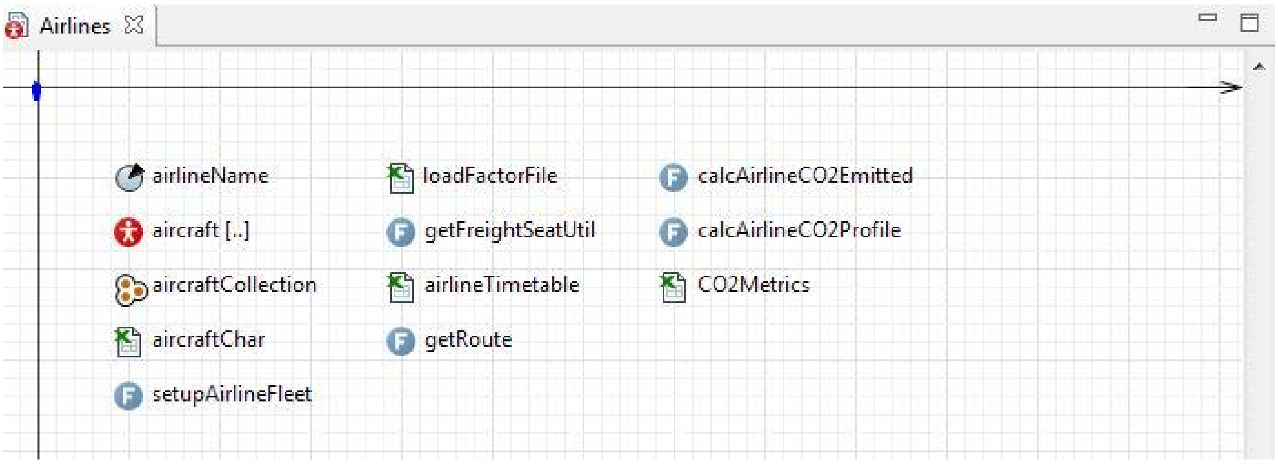
Yin, K.-s., Dargusch, P., & Halog, A. (2015). An analysis of the greenhouse gas emissions profile of airlines flying the Australian international market. *Journal of Air Transport Management*, *47*, 218-229. doi: http://dx.doi.org/10.1016/j.jairtraman.2015.06.005

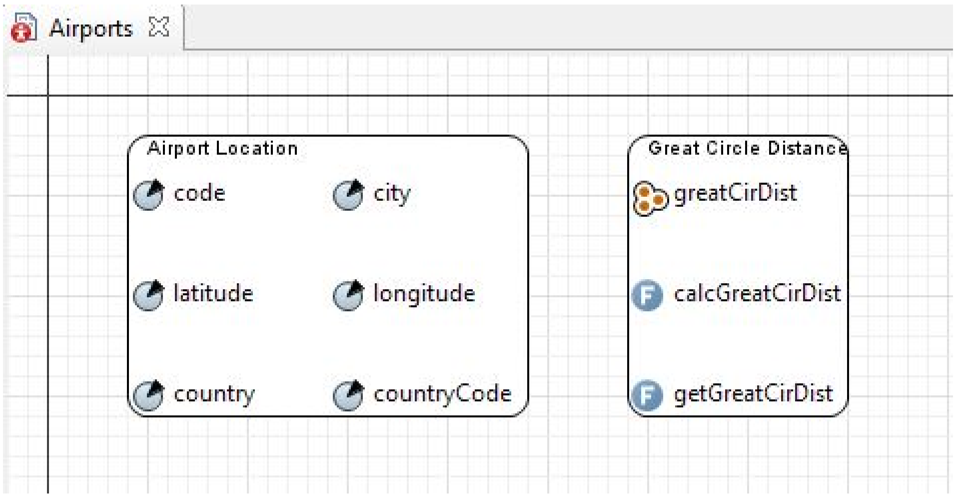
Yin, K.-s., Dargusch, P., & Halog, A. (2016). A study of the abatement options available to reduce carbon emissions from Australian international flights. *International Journal of Sustainable Transportation*, *10*, 935-946. doi: 10.1080/15568318.2016.1190882

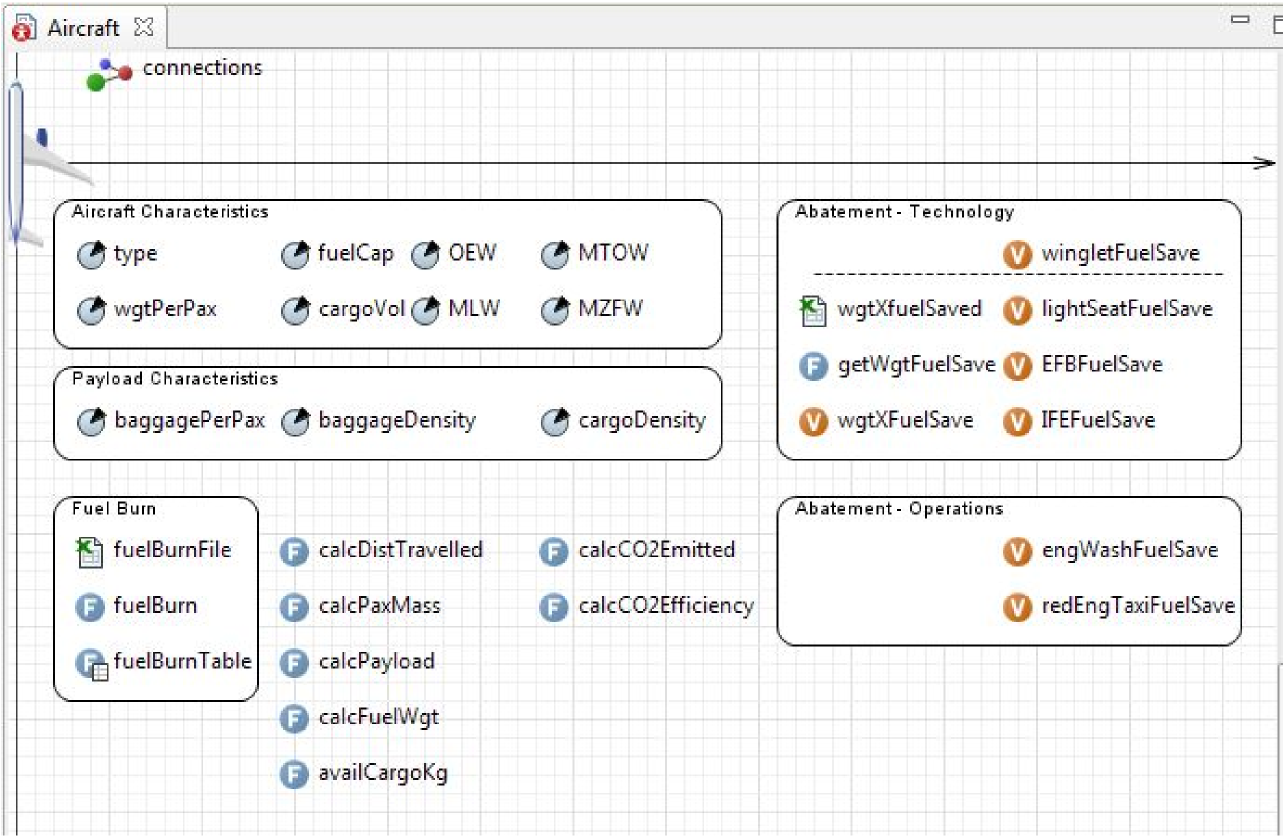
Appendix A. **AnyLogic Model**

Screenshot of the AnyLogic model






Airports
Airport Location
code
city
latitude
longitude
country
countryCode
Great Circle Distance
greatCirDist
calcGreatCirDist
getGreatCirDist


Aircraft
connections
Aircraft Characteristics
type
fuelCap
OEW
MTOW
wgtPerPax
cargoVol
MLW
MZFW
Payload Characteristics
baggagePerPax
baggageDensity
cargoDensity
Abatement - Technology
wingletFuelSave
wgtXfuelSaved
lightSeatFuelSave
getWgtFuelSave
EFBFuelSave
wgtXFuelSave
IFEFuelSave
Fuel Burn
fuelBurnFile
fuelBurn
fuelBurnTable
calcDistTravelled
calcPaxMass
calcPayload
calcFuelWgt
availCargoKg
calcCO2Emitted
calcCO2Efficiency
Abatement - Operations
engWashFuelSave
redEngTaxiFuelSave

Appendix B. Input data set for the AnyLogic model (six Excel spreadsheets).

Below are screenshots of each Excel input data set.

Airport Location

	A	B	C	D	E	F
1	Country	Country Cod	City	Airport Code	Latitude	Longitude
2	Australia	AU	Sydney	SYD	-33.9329	151.1799
3	Australia	AU	Melbourne	MEL	-37.6696	144.8498
4	Australia	AU	Brisbane	BNE	-27.403	153.109
5	Australia	AU	Adelaide	ADL	-34.9382	138.5373
6	Australia	AU	Perth	PER	-31.9336	115.9602
7	Australia	AU	Gold Coast	OOL	-28.1661	153.5131
8	Australia	AU	Cairns	CNS	-16.8765	145.754
9	Australia	AU	Darwin	DRW	-12.4078	130.8775
10	Australia	AU	Sunshine Co	MCY	-26.6054	153.0882
11	Australia	AU	Port Hedlanc	PHE	-20.3779	118.6316
12	USA	US	Guam	GUM	13.4928	144.8049
13	USA	US	Los Angeles	LAX	33.9434	-118.4083
14	USA	US	San Francisc	SFO	37.6152	-122.3899
15	USA	US	Dallas	DFW	32.8975	-97.0361
16	USA	US	Honolulu	HNL	21.3258	-157.9217
17	Singapore	SG	Singapore	SIN	1.3612	103.9902
18	United Arab	AE	Dubai	DXB	25.2487	55.3529
19	United Arab	AE	Abu Dhabi	AUH	24.4269	54.646

Airline Load Factor in 2012

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	2012		Inbound						Outbound					
2	Month	Service tc	No. of	Pax	Seats	Seat	Freight	Mail	No. of	Pax	Seats	Seat	Freight	Mail
3			Flights	Carried	Available	Utilisatioı	(tonnes)	(tonnes)	Flights	Carried	Available	Utilisatioı	(tonnes)	(tonnes)
4	1	Hong Kon	332	80706	85636	94.24308	2898.469	206.726	332	68877	85636	80.42996	3368.665	17.567
5	2	Hong Kon	310	70753	80041	88.39595	2641.13	167.579	310	52789	80064	65.9335	2653.025	18.347
6	3	Hong Kon	329	59714	84899	70.33534	3984.032	208.615	328	61425	84633	72.57807	2574.558	20.965
7	4	Hong Kon	309	61908	77236	80.15433	3636.591	215.518	310	65157	77500	84.07355	2368.06	31.054
8	5	Hong Kon	314	45301	77749	58.2657	3615.372	199.167	313	51933	77468	67.038	2661.035	23.67
9	6	Hong Kon	301	49692	74726	66.49894	4034.374	182.589	300	61659	74481	82.78487	2065.285	20.567
10	7	Hong Kon	312	70483	77021	91.51141	4536.594	196.942	308	47206	75924	62.17533	1975.503	20.653
11	8	Hong Kon	313	55980	75932	73.72386	4464.77	209.485	312	62556	75713	82.62254	1951.74	21.11
12	9	Hong Kon	305	57625	74750	77.0903	3521.799	169.287	304	56969	74486	76.48283	2300.243	18.241
13	10	Hong Kon	315	62794	74679	84.08522	4265.376	168.598	316	51748	74943	69.04981	2190.833	21.441
14	11	Hong Kon	300	53257	70658	75.37292	4200.26	220.36	300	59437	70658	84.11928	2382.902	22.201
15	12	Hong Kon	317	59521	75929	78.39034	3721.218	299.534	316	69812	75678	92.24874	3511.411	41.769
16														
17														
18														
19														

Etihad | Cathay Pacific | Delta Air Lines | Emirates | Virgin Australia | Jetstar | Qantas Airways | Singapore Airlines | Malaysia Airlines

Airline Timetable in 2012

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Org	Org State	rg Countr	Dst	Dst State	st Countr	Al	Equip	Flights	Seats	Flights	Seats	Flights	Seats	Flights	Seat
2	Hong Kong		HK	Brisbane	QL	AU	Qantas A	A330-200 (A330 - Wide Airbus)								
3	Hong Kong		HK	Brisbane	QL	AU	Qantas A	A330-300 (A33(	18	5,346	17	5,049	16	4,752	17	5,04
4	Hong Kong		HK	Brisbane	QL	AU	Qantas A	B747-400 Passenger (B747 - Wide Boeing)					1	394		
5	Hong Kong		HK	Melbourn	VI	AU	Qantas A	A330-200 (A330 - Wide Airbus)								
6	Hong Kong		HK	Melbourn	VI	AU	Qantas A	A330-300 (A330 - Wide Airbus)					8	2,376	30	8,91
7	Hong Kong		HK	Melbourn	VI	AU	Qantas A	B747-400 Passe	31	12,214	29	11,426	23	9,062		
8	Hong Kong		HK	Perth	WA	AU	Qantas A	A330-200 (A330 - Wide Airbus)								
9	Hong Kong		HK	Perth	WA	AU	Qantas A	A330-300 (A33(	14	4,158	11	3,267	12	3,564	12	3,56
10	Hong Kong		HK	Sydney	NS	AU	Qantas A	A330-200 (A33(	5	1,515	3	909	2	606	1	303
11	Hong Kong		HK	Sydney	NS	AU	Qantas A	A330-300 (A33(	15	4,455	13	3,861	13	3,861	16	4,75
12	Hong Kong		HK	Sydney	NS	AU	Qantas A	A380-800 Passe	11	4,950	16	7,200	19	8,550	17	7,65
13	Hong Kong		HK	Sydney	NS	AU	Qantas A	B747-400 Passe	20	7,880	13	5,122	14	5,516	13	5,12
14	Jakarta		ID	Sydney	NS	AU	Qantas A	A330-200 (A330 - Wide Airbus)								
15	Jakarta		ID	Sydney	NS	AU	Qantas A	A330-300 (A33(	18	5,346	17	5,049	15	4,455	18	5,34
16	Auckland		NZ	Brisbane	QL	AU	Qantas A	B737-800 Wing	62	10,416	58	9,744	58	9,744	60	10,08
17	Auckland		NZ	Melbourn	VI	AU	Qantas A	B737-800 Wing	93	15,624	87	14,616	93	15,624	90	15,12
18	Auckland		NZ	Sydney	NS	AU	Qantas A	A330-200 (A33(	18	5,454	16	4,848	18	5,454	17	5,15
19	Auckland		NZ	Sydney	NS	AU	Qantas A	B737-800 Wing	136	22,848	128	21,504	131	22,008	132	22,17
20	Christchurch		NZ	Sydney	NS	AU	Qantas A	B737-800 Wing	31	5,208	29	4,872	31	5,208	30	5,04
21	Christchurch		NZ	Sydney	NS	AU	Qantas A	B767-300 Passenger (B767 - Wide Boeing)								
22	Queenstown		NZ	Brisbane	QL	AU	Qantas A	B737-800 Winglets Pax/BBJ2 (B737-6/7/8/9 - Narrow Boeing)								

Etihad | Garuda | Jetstar | Malaysia Airlines | **Qantas Airways** | Singapore Airlines | United Airlines | Virgin Australia | Hawaiian Airline

Aircraft Characteristics

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Aircraft	Vers	MTOW(kg)	MTOW(lb)	OEW(kg)	OEW(lb)	MLW(kg)	MLW(lb)	MZFW(kg)	MZFW(lb)	Fuel Cap(L)	Fuel Cap(US	Cargo Vol ((
2	B737-700	Mid Wgt(CFM56-7B) + winglet	69400	153000	37648	83000	58060	128000	54658	120500	26022	6875	27.4
3	B737-800	Mid Wgt(CFM56-7B) + winglet	78245	172500	41413	91300	65317	144000	61689	136000	26022	6875	44.1
4	B777-300ER	Maximum	351535	775000	167829	370000	251290	554000	237683	524000	181283	47890	213.8
5	F-100	Tay 650	45810	101000	24747	54558	39915	88000	36740	81000	13365	3531	16.72
6													
7		http://www.virginaustralia.com/au/en/experience/on-board-the-flight/our-fleet/											
8		http://www.brisbanetimes.com.au/business/aviation/virgin-gets-boost-from-air-new-zealand-alliance-20141208-121dsm.html											
9													
10													

Sheet1 | Qantas Airways | Jetstar | **Virgin Australia** | Singapore Airlines | Emirates | Delta Air Lines | United Airlines | AirAsia X | Air

Fuel Burn tables from CORINAIR

A1 | *fx* | A320(737-800/900) CORINAIR data raise by 4.2%

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	A320(737-800/900) CORINAIR data raise b				1.042			**CORINAIR spreadsheet in http://www.eea.europa.eu/publications/EMEPC**						
2	**A320new**		Standard flight distance	Standard flight distances (nm)				**CORINAIR data modified as recommended by the report "Future Aircraft Fuel Effic**						
3			**125**	**250**	**500**	**750**	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**		
4														
5	**Distance (km)**													
6		Climb/cruis	231.50	463.00	926.00	1389.00	1852.00	2778.00	3704.00	4630.00	5556.00	6482.00		
7	**Fuel (kg)**													
8		Flight total	1713.457	2602.1803	3814.351	4902.617	6280.371	8681.957	11322.26	14005.8	16491.08	19149.77		
9		LTO	836.0301	836.03011	836.0301	836.0301	836.0301	836.0301	836.0301	836.0301	836.0301	836.0301		
10		Taxi out	174.3212	174.32119	174.3212	174.3212	174.3212	174.3212	174.3212	174.3212	174.3212	174.3212		
11		Take off	93.66917	93.669169	93.66917	93.66917	93.66917	93.66917	93.66917	93.66917	93.66917	93.66917		
12		Climb out	242.2302	242.23017	242.2302	242.2302	242.2302	242.2302	242.2302	242.2302	242.2302	242.2302		
13		Climb/cruis	877.4267	1766.1502	2978.32	4066.587	5444.341	7845.927	10486.23	13169.77	15655.05	18313.74		
14		Approach l	151.4884	151.4884	151.4884	151.4884	151.4884	151.4884	151.4884	151.4884	151.4884	151.4884		
15		Taxi in	174.3212	174.32119	174.3212	174.3212	174.3212	174.3212	174.3212	174.3212	174.3212	174.3212		
16														
17		C02(kg)	5409.383	8215.0831	12041.9	15477.56	19827.13	27408.94	35744.39	44216.3	52062.32	60455.82		
18	3.157	kg/km	23.36667	17.74316	13.00422	11.14295	10.70579	9.866428	9.650213	9.549957	9.370469	9.326724		
19														

B747-400 | **A320** | A320NEO | A321 | A340 | A350 | A380 | B737-700 | B767 | B777-300ER | B787 | B747-8 | F-100 | Summary

Fuel saved due to weight savings according to Boeing and Airbus

	A	B	C	D	E	F	G	H	I	J
25	Airbus-Boeing estmates of fuel savings.									
26			Weight change kg (1000lb)	Typical Sector (nm)	Fuel burn in typical Sector from updated CORINAIR (kg)	Weight Increase (kg)	Fuel Penalty per sector (kg)	Fuel Penalty (%) per 1000lbs (454kg)	Fuel Penalty (%) per kg	Trips per day
27	A320		454	1000	6280.37	735.00	60.00	0.590%	0.001300%	4.47368
28	A321		454	1000	7272.67	890.00	55.00	0.386%	0.000850%	4.47368
29	B737-700		454					0.600%	0.001322%	3.69565
30	B737-800		454					0.600%	0.001322%	3.69565
31	B737-400							0.600%	0.001322%	
32	A330-200		454	4000	51005.69	2300.00	460.00	0.178%	0.000392%	2.60465
33	A330-300		454	4000	51005.69	2300.00	440.00	0.170%	0.000375%	2.60465
34	B767-300		454					0.300%	0.000661%	2.31818
35	A340-300		454	6000	113821.10	2535.00	1330.00	0.209%	0.000461%	1.47826
36	A340-600		454	6000	113821.10	3650.00	1420.00	0.155%	0.000342%	1.47826
37	B777-200		454					0.200%	0.000441%	2.09434
38	B777-300		454					0.200%	0.000441%	2.09434
39	B747-400		454					0.200%	0.000441%	2.0566
40	B747-400ER							0.200%	0.000441%	
41	F-100							0.000%	0.000000%	
42	A380-800							0.200%	0.000441%	
43	B737-300							0.000%	0.000%	
44	A340-500		454	6000	113821.10	3680	1410	0.153%	0.000337%	