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When will biofuels be economically feasible for commercial flights? Considering the difference between environmental benefits and fuel purchase costs

Cherie Lu*

Department of Aviation and Maritime Management, Chang Jung Christian University, Tainan, Taiwan

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ABSTRACT

This paper evaluates the financial outlays and environmental costs of using biofuel and traditional aviation fuel for selected flight routes. Cost-benefit analysis and the dose-response method were applied for evaluating the financial and environmental costs of both biofuels and traditional fuel. Selected flight routes originating from Taipei were used for empirical analysis, for the purpose of comparing the use of different fuels in monetary terms. The use of biofuel leads to a considerable increase in fuel purchase price; however, it results in fewer negative environmental impacts compared with the use of the traditional aviation fuel. The empirical results and sensitivity analysis show that the reduction in environmental costs will only outweigh the additional purchase cost of biofuel if the unit environmental social costs of pollutants are considered to be very high. The potential incentives for the use of biofuel in commercial flights could come from some form of government measures that internalize externalities, or from a reduction in biofuel price (e.g. through subsidy) or an increase in traditional fuel price (e.g. through tax). The environmental benefit of using biofuel in commercial flights, estimated in monetary terms and compared with its extra financial cost, provide good reference for policy makers when implementing policies and incentives for the development of biofuels.

1. Introduction

With increasing economic development, the environmental impacts that an industry brings have gained increasing attention. Air transport, as a highly energy-consuming transport mode, is certainly at the heart of international discussion on sustainable development.

Current commercial aircraft are powered by the combustion of jet-fuel which is derived from fossil crude oil and the commercial aviation sector is a major contributor to global warming and air pollution, generating around 2% of global man-made carbon dioxide emissions, and this is expected to reach around 4% by 2050 (IPCC, 2014). The quantity of jet-fuel consumed is expected to greatly increase with the high growth rate of air traffic demand, which is forecast to increase at an average annual rate of around 5–6%, despite the economic downturn, with the Asian region having the highest growth rate of all (Boeing, 2015). This means that the extent of global air pollution and climate change due to the aviation industry should also increase if measures are not taken.

To accommodate this traffic with limited environmental impact, the airline industry is committed to cutting its carbon emissions by half by 2050 compared with the 2005 level (IATA, 2016). Moreover, besides the climate-change implications of carbon dioxide (CO_2), air pollutants such as nitrogen oxides (NOx), carbon monoxide (CO), and unburnt hydrocarbons (HC), emitted during the combustion of jet-fuel, affect local air quality.

For aviation, in addition to improvements to aircraft/engine technology, air navigation and airport infrastructure and operations, and market-based measures, the use of alternative fuel plays a vital role in achieving this goal. Biofuels, which can be renewable, low-carbon, environmentally friendly, and clean, are considered to be the most promising alternative fuels for the aviation sector (Wise et al., 2017; IEA, 2011). Apart from alleviating environmental impacts, the development of alternative fuels will also contribute to increasing the security of the jet-fuel supply needed for the rapid growth of the aviation industry (Bogers, 2009; EC, 2012).

Of all of the alternative fuel concepts currently under development, those which are drop-in compatible with traditional

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* 1 Changda Road, Gueiren District, Tainan City, 71101, Taiwan.
E-mail address: cherie@mail.cjcu.edu.tw.

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kerosene have had the most rapid uptake, with many currently certified to ASTM D1655[1] equivalent for blending up to 50% with Jet-A1. Although these are not necessarily produced from bio feedstocks, they are generally referred to as “biofuels”. The first successful biofuel test flight was by Virgin Atlantic in February 2008. In June 2011, KLM operated the first biofuel flight with passengers onboard (using used cooking oil) on a Boeing 737 from Amsterdam to Paris. In 2011, Lufthansa was the world’s first airline to test the use of biofuel in regular operations on more than 1100 scheduled flights in the second half of 2011 (IATA, 2012b). Since then there have been many airlines operating more than 2500 flights, around the globe that have used various kinds of biofuel either for the test flights, or on regular scheduled flights (ICAO, 2016). The most commonly used feedstocks for biofuels in the aviation industry have been jatropha, camelina, used cooking oil, waste and algae (Kagan, 2010; ATAG, 2011; Blakey et al., 2011).

Given the fast growth in biofuel usage in the aviation industry, the International Civil Aviation Organization (ICAO) established the sustainable aviation alternative fuel (SUSTAF) Expert Group for the purpose of promoting the application of sustainable alternative fuels and encouraging member states to develop related projects and to give suggestions (ICAO, 2011). The International Air Transport Association (IATA) has also published annual alternative fuel reports since 2009. Various aviation-related organizations have been working together and looking into the issues from different aspects (IATA, 2012a). While reviewing the cases of biofuel flights, the related issues that need to be investigated or developed include national alternative transport-fuel policies, technology research, supply of feedstock, fuel qualification and certification, deployment, public-private partnerships and cooperation, framework of laws and regulations, life-cycle analysis and sustainability as well as financial resources etc. (ICAO, 2011; Lin and Huang, 2013; Arvidsson et al., 2012; Reimer and Zheng, 2017). Of all the related issues, however, the fundamental question to explore is whether the use of biofuel generates more benefits than costs from both the environmental and financial points of view, given current scientific knowledge.

This research aims to evaluate the financial expense and environmental costs of using biofuel and traditional aviation fuel for selected flight routes. In the current market situation, the purchasing cost of biofuel is generally higher than that of fossil fuel. However, it is generally recognized that burning biofuel emits less exhaust pollutants than burning fossil fuel (IATA, 2016; ICAO, 2016). By comparing the difference in purchase cost between biofuel and Jet A1 fuel, and the reduction in the environmental social cost, which can be considered an environmental benefit, one can obtain insights into whether the use of biofuel is more economical from the social point of view. The current low crude oil price, which reflects on Jet A1 fuel price as well, is likely to jeopardize the development and use of biofuels. Hence, the sensitivity analysis will explore further in which circumstances the use of biofuel could be feasible compared with traditional fuel.

This paper first explores the key issues of biofuel applications in the aviation industry. A cost-benefit analysis and the dose-response method are then applied for evaluating the financial and environmental costs of substituting biofuels for traditional fuel, using selected flight routes originating from Taipei. Further discussion on the potential implementation and policy implications of biofuel is then given in Section 4, followed by conclusions and recommendations.

2. Environmental cost of fuel emissions

The amount of aircraft engine emissions from flights varies by aircraft operation, engine type, emission rate, flying and cruise time, and even the level of airport congestion etc. Exhaust emissions at ground level resulting from the landing and take-off (LTO) phases of flight is distinguished from the cruise level impact, and therefore analyzed separately in this research, as the damage pattern and magnitude are different between these two phases of flight.

A number of articles in the literature have dealt with the impacts of exhaust pollutants from different aspects. The most commonly discussed impacts are on human health and climate change (EUROCONTROL, 2005). Of all the pollutants emitted from aircraft engines, six - particulates (PM), oxides of sulfur (SO_X), NO_X, HC, CO and CO_2 - have been found to have different degrees of negative implications for human health, with PM having the highest unit cost and CO_2 the lowest. However, CO_2 has the highest volume emitted during flights.

The climate change impact from the cruise phase of a flight is complex and only the cost of CO_2 emissions has been included here. Three pollutants in particular - CO_2, NO_X and H_2O - which are considered GHGs and result in climate change, are discussed in the literature (Snijders and Melkert, 2011). The impact of CO_2 on climate change has been recognised worldwide (US FAA, 2012). Other pollutants emitted during the cruise stage are generally non-linear to fuel burn (EUROCONTROL, 2015). However, there are already existing available models, such as the IMPACT model from European Organisation for the Safety of Air Navigation (EUROCONTROL) and US Federal Aviation Administration’s (FAA) Aviation Environmental Design Tool (AEDT), which include more exhaust pollutants for the cruise stage using industry-provided data.

There are different approaches to evaluating the environmental impacts, varying from global scales (Daly, 2007; Costanza et al., 2014) to impacts of individual pollutants. This paper aims to estimate the aggregated impacts of each pollutant during flights; therefore, the dose-response technique is applied. This is considered a comprehensive method for evaluating the damage resulting from aircraft engine exhaust pollutants (Pearce and Markandya, 1989). This is done by estimating the environmental costs imposed through the damage on human health, vegetation, buildings, and climate change and global warming, based on the dose-response relationships between pollution and effects, and then summing the individually derived monetary result. A summary of scientific findings to date on the unit social costs per pollutant is given in Table 1 (€/kg); where results are expressed in ranges, these are the minimum and maximum values. As the monetary evaluation of the damage is still uncertain (as is reflected in the wide range of monetary impacts), the unit social cost estimates for each pollutant have been averaged across all the studies for use in the later empirical analysis (Lu, 2011). It would be better to adjust the unit social cost for specific airports but it is impossible to achieve this with the scientific results that have been published to date.

The social costs for individual aircraft movements with specific engine types and standard flight modes can be derived, applying the average unit social cost for each pollutant listed in Table 1 to fuel flow and emissions data for the various phases of flight (ICAO, 2015).

F_{ijk}, the amount (kilograms) of the jth pollutant emitted during the ith flight mode for the kth fuel, can be derived from the following formula:

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[1] Standard specification for aviation turbine fuels.

Table 1
The unit social costs (in 2015 euros) of 6 different exhaust pollutants per kg.

	CO_2	HC	CO	NO_X	SO_X	PM
Dhar et al. (2009)	0.04	–	–	–	–	–
ExternE-Pol (2005)	0.02	–	0.03–0.06	2.90–3.2	2.90–10.73	319.50–600.00
Gallagher and Taylor (2003)	–	–	0.19	1.00–12.00	1.00–3.00	–
Schipper (2004)	–	0.72–13.76	–	1.88–38.10	1.53–40.99	5.09–107.25
Average	0.03	8.86	0.06	11.83	12.26	292.88

Source: compiled by the author.

$$F_{ijk} = t_i f_i e_{ijk} \tag{1}$$

where t_i is the time spent during the ith mode (hours); f_i is the fuel flow during the ith mode (kg/hr) (assuming the fuel flows for both traditional fuel and biofuel are the same); e_{ijk} is the emission index of the jth pollutant during the ith mode (kg pollutant/kg fuel) for the kth fuel. The calculation of C_{em}, the social cost per flight for the mth aircraft/engine combination ($/flight) is:

$$C_{emk} = \sum_{j=1}^{6} \sum_{i=1}^{5} \alpha_{ij} F_{ijk} U_j \tag{2}$$

where α_{ij} is the damage multiplier factor for pollutant j, in flight mode i. For this research, $\alpha_{ij} = 1$ is used for the CO_2 emissions during both LTO and cruise (which means the pollutant causes the same damage whatever the flight mode), and for all other pollutants during LTO stages only, otherwise $\alpha_{ij} = 0$. U_j is the unit social cost for the jth pollutant ($/kg).

Five operational modes are calculated separately, namely taxi/idle, take-off, climb-out, cruise, and approach. The six exhaust pollutants listed in Table 1 are considered.

3. The comparison of biofuel and traditional fuel – financial and environmental costs

3.1. Selected flight routes and fuel consumption

Three flight routes, which represent some of the most popular routes from Taiwan Taoyuan International Airport (TPE), have been chosen for the empirical analysis: Paris Charles de Gaulle (CDG), Singapore Changi (SIN) and Hong Kong Chek Lap Kok (HKG) airports. These are considered to be representative long-haul, medium-haul and short-haul routes. The flight characteristics (in Table 2) are taken from typical Taiwanese airlines' information, including aircraft type, engine type, flight distance, cruise attitude and flight time. The B777-300 E R is used for both long-haul and medium haul flights, showing that the Asian airlines tend to use larger aircraft for comparatively shorter flight distances, as opposed to European and American airlines. Different cruise speeds result in different quantities of fuel used, and commercial flights will generally cruise with the most fuel-efficient speed. The cruise speeds for the B777-300 ER and the A330-200 are assumed therefore to be 0.84 and 0.82 Mach respectively as these are the common cruise speed by airlines for these aircraft types.

The fuel consumption for the LTO and cruise stages, based on the existing fuel flow data (ICAO, 2015; EUROCONTROL, 2004), are listed in Table 3 by different flight routes, assuming the standard flight procedures of engine thrust and time for each flight stage. LTO flight operation is that below 3000 feet. In addition, the fuel used for the rest of a flight is estimated using the cruise stage parameters. Since the ICAO standard LTO procedures are applied, the LTO fuel consumption is be the same value for the same aircraft type (i.e. B777-300 E R for TPE-CDG and TPE-SIN).

3.2. Environmental costs of biofuel and traditional fuel

For traditional fuel, the emissions indices, emissions emitted per unit of fuel consumed, for CO, HC, and NO_X are taken from ICAO (2015) (see Appendix). The emission index for CO_2 is 3.157 kg/kg fuel (ICAO, 2014). Those for SO_2 and PM are taken as 0.84 and 0.2 g/kg fuel respectively (EUROCONTROL, 2005, 2015). Further adjustments can be made when the non-linear or standardized emission indices are publicly available. The different emissions per flight for both cruise and LTO stages are listed in the first half of Table 4.

For the various biofuel trials that have taken place around the globe with different airlines and feedstocks, the fuel and emission data are generally confidential to airlines and the parties involved, and the engine performance will vary according to different feedstocks (Azami and Savill, 2017).

However, Boeing has completed a test flight using a biodiesel

Table 2
Airline's flight characteristics for the case study.

Origin- destination	Aircraft type	Engine type	Flight distance (km)	Flight attitude (feet)	Flight time (hours)
TPE-CDG	Boeing 777-300 E R	GE90-115 B	11,318	37,000	13.5
TPE-SIN	Boeing 777-300 E R	GE90-115 B	3270	35,000	3.56
TPE-HKG	Airbus 330-200	CF6-80E1A3	903	31,000	1.16

Source: compiled by the author, from airlines' flight information.

Table 3
Fuel consumption for LTO and cruise stages.

Aircraft type (flight route)	LTO (kg/flight)	Cruise (kg/flight)	Total (kg/flight)
B777-300 E R (TPE-CDG)	3091	179,187	182,278
B777-300 E R (TPE-SIN)	3091	52,941	56,032
A330-200 (TPE-HKG)	1217	13,225	14,442

Source: estimated by the author.

Table 4
LTO and cruise emissions for different flights with traditional fuel and biofuel.

Fuel	Flight stage	Cruise	LTO					
	Emissions (kg/flight)	CO_2	CO_2	HC	CO	NO_X	PM	SO_2
Tradi-tional	B777-300 E R (TPE-CDG)	565,694	9758	5.1	47.5	69.8	0.6	2.6
	B777-300 E R (TPE-SIN)	167,136	9758	5.1	47.5	69.8	0.6	2.6
	A330-200 (TPE-HKG)	41,750	3842	6.8	26.5	19.9	0.2	0.2
Bio (B100)	B777-300 E R (TPE-CDG)	122,756	2117	2.2	27.0	73.8	0.3	0.0
	B777-300 E R (TPE-SIN)	36,269	2117	2.2	27.0	73.8	0.3	0.0
	A330-200 (TPE-HKG)	9060	834	3.0	15.0	21.1	0.1	0.0

Source: estimated by the author.

Table 5
Emission reduction for biodiesel compared with fossil fuel.

Emissions	100% biodiesel (B100)	20% biodiesel (B20)
CO	−43.2%	−12.6%
CO_2	−78.3%	−15.7%
HC	−56.3%	−11.0%
PM	−55.4%	−18.0%
NO_X	+5.8%	+1.2%
SO_X	−100%	−20.0%

Source: Bart et al. (2010), compiled by the author.

blend, which demonstrated the use of green biodiesel for aviation (ICAO, 2016). Therefore, the emissions reduction rate used in the analysis is that for biodiesel compared with traditional fuel. This will obviously bring a certain level of inaccuracy to this analysis but the accuracy of the estimation can be improved when actual biofuel combustion data are publicly available. Based on (Bart et al., 2010), comparing the emission performance of biodiesel with traditional fuel, nitrogen oxides (NOx) might increase by 1.2% in the case of B20 biodiesel (the biodiesel is blended with petro-diesel at 20% by volume), and 5.8% for B100 (100% biodiesel). However, for B100 the reduction in SO_X could reach as much as 100.0%, meaning no SO_X is emitted. Biofuel blends also result in reductions for the other pollutants as seen in Table 5.

Making the general assumption that the fuel efficiency and the volume of fuel consumed for biofuel is the same as that of traditional fuel, the second half of Table 4 lists the emissions emitted using B100 biofuel. Although most of the biofuel flights at the moment are blended in with traditional fuel in various proportions up to 50% (Lemus, 2013), the application of B100 aims to illustrate the environmental benefit of biofuel to its maximum extent.[2] Simply applying the reduction rates from Table 5 to the figures of traditional fuel in Table 4 provides the emissions emitted from biofuel usage for different flight routes listed in the lower half of Table 4.

Taking the emission data in Table 4, multiplied by the unit environmental costs in Table 1, the environmental costs for different pollutants and in the aggregation level are shown in Table 6 as well as in Fig. 1.

3.3. Comparison of financial costs and environmental benefits of biofuel and traditional fuel

The price of biofuel varies enormously depending on the kind of feedstock used, production method, and quantity purchased, as well as geographical location etc. According to the IATA Report on Alternative Fuels (IATA, 2014), the U.S. military has purchased around 7.2 million litres (1.9 million US gallons) of various kinds of biofuel through its procurement agency DLA Energy. This might serve as a good reference regarding the actual purchase prices of biofuels. The biofuel prices range from a low of US$0.99/litre for Synthetic Paraffinic Kerosene (SPK) produced from natural gas and coal fuel using the Fischer-Tropsch (FT) method, to US$10.11/litre for Hydroprocessed Renewable Jet/Hydroprocessed Esters and Fatty Acids (HRJ/HEFA) fuel produced from camelina, algal oil, used cooking oil and tallow.

FT-SPK and HRJ/HEFA are the most commonly used methods for deriving alternative fuels. Based on the case studies of the airlines that have operated biofuel scheduled flights or pilot flights, biofuels used are most often derived from the feedstocks such as camelina and used cooking oil. A case from an airline's purchase (according to Southwest Airlines announcement in September 2014) showed a price of around US$0.79/litre (US$3.00/gallon) for fuel from woody biomass produced using a FT process (IATA, 2014). In addition, a recent study (Winchester et al., 2013) estimated that HEFA jet fuel from rotation crops in the U.S. such as camelina and pennycress could be produced at around US$0.98/litre (US$3.70/gal), which is much lower than the previous reference shown. Research by Tzanetis et al. (2017) found that by applying the method of biomass hydrothermal liquefaction, a biofuel could be produced at a cost of twice that of commercial jet fuel. However, the life-cycle CO2 emissions could be reduced by 85%.

The price of jet fuel has been quite unstable for the past 10 years, with a highest monthly average price of 1.03 US$/litre in July 2008, followed by a dramatic decline in 2009 and again from 2014 onwards, to hit a monthly average low point of 0.26 US$/litre in February 2016 (Fig. 2). The average jet fuel price from this data set is 0.63 US$/litre.

Again, assuming the fuel efficiency of biofuel to be the same as that of traditional fuel, the purchase costs for traditional fuel and biofuels, in euros per flight, are listed in Table 7, taking the average biofuel price of US$1.00/litre as the base case, using the fuel consumption per flight given in Table 3 and a fuel density of 0.81 kg/L. These figures are then compared with the environmental benefits of replacing traditional fuel with biofuel, namely the difference in environmental costs of the two. The extra purchase cost and the environmental benefit of using biofuel is shown in Table 7.

Based on this base case, the difference between extra purchase cost and environmental benefits is illustrated in Fig. 3. The cost benefit ratios for these routes range from 5.23 to 5.50, meaning that use of biofuel is not economical for the index concerned. The threshold for using biofuel is further explored in the sensitivity analysis.

Source: derived from U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price (United States Energy Information Administration, 2016).

The general public is gradually becoming aware of biofuel technology, although knowledge of the environmental benefits biofuel brings is limited (Filimonau and Högström, 2017). Comparing these environmental benefits and extra purchase costs with airfares could help our understanding of the impact of changing fuel on these fares.

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[2] The National Research Council of Canada (NRC) conducted a test flight with a Falcon 20 using 100% biofuel in October 2012 (ICAO, 2016).

Table 6
Environmental costs for traditional fuel and biofuel (€/flight).

Flight originating from TPE	Traditional fuel			Biofuel (B100)		
	To CDG	To SIN	To HKG	To CDG	To SIN	To HKG
CO_2	17,264	5307	1368	3746	1152	297
HC	45	45	60	20	20	26
CO	3	3	2	2	2	1
NO_X	826	826	263	874	874	249
SO_2	32	32	3	0	0	0
PM	181	181	71	81	81	32
Total	**18,350**	**6393**	**1739**	**4722**	**2127**	**605**

Source: compiled by the author.

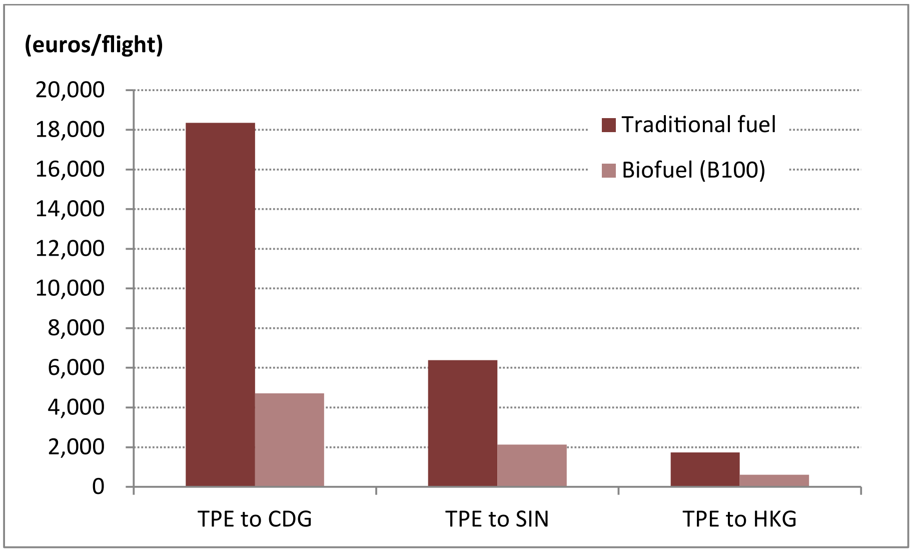

Fig. 1. Environmental cost comparison of traditional fuel and biofuel for different flight routes.

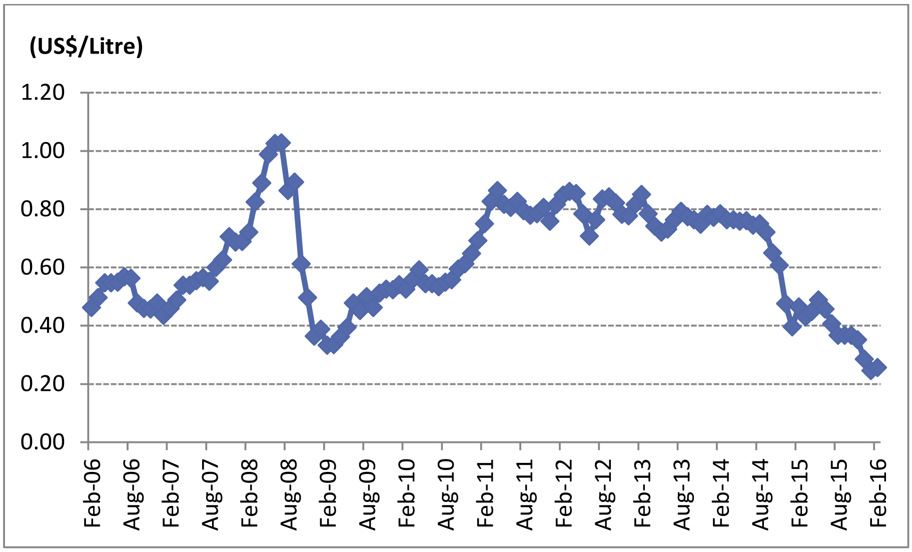

Fig. 2. Trend of monthly average jet fuel price from Feb 2006 to Feb 2016.

The numbers of seats for the three routes TPE to CDG/TPE to SIN/TPE to HKG are taken as 353/323/252, using a typical seat configuration of these aircraft types by Taiwanese airlines, using an average load factor of 80%. The average one-way economy flexible ticket fares are €140, €220 and €560 respectively.

The extra fuel purchase costs for switching from traditional fuel to biofuel is equivalent to 47%, 41% and 21% of the average one-way economy flexible ticket fares respectively for these routes (Fig. 4). However, the environmental benefits (i.e. the reduction in emissions) are equivalent to just 9%, 8% and 4% respectively. It may be considered unlikely that passengers would be willing to pay such a high premium for such little environmental gain.

Table 7
The purchase cost of traditional fuel and biofuel (euros/flight).

Fuel type	Flight route		
	TPE to CDG	TPE to SIN	TPE to HKG
Traditional fuel at 0.63 US$/litre	127,595	39,223	10,109
Biofuel at US$1.00/litre	202,531	62,258	16,046
Biofuel extra purchase cost	74,936	23,035	5937
Environmental benefit	13,628	4266	1134

Source: derived by the author. Note: The 2015 average EU/US exchange rate from European Central Bank of 0.91 is used.

3.4. *Sensitivity analysis*

If environmental cost is internalised through market-based measures, such as CORSIA, emission charges/trading or fuel surcharges, this environmental cost then becomes part of the actual financial cost of using the fuel; the fuel usage cost is the aggregation of fuel purchase cost and environmental cost.

The sensitivity analysis will be examining the following three aspects of the fuel usage costs, using TPE-HKG as the base case:

- A change in unit environmental costs;
- A change in biofuel price;
- A change in traditional fuel price.

An increase in unit environmental costs of both biofuel fuel usage cost and traditional fuel usage cost is shown in Fig. 5. As the unit environmental cost increases, the traditional fuel usage cost increases much more sharply than the biofuel one, reflecting the higher emission rates from traditional fuel. When the unit

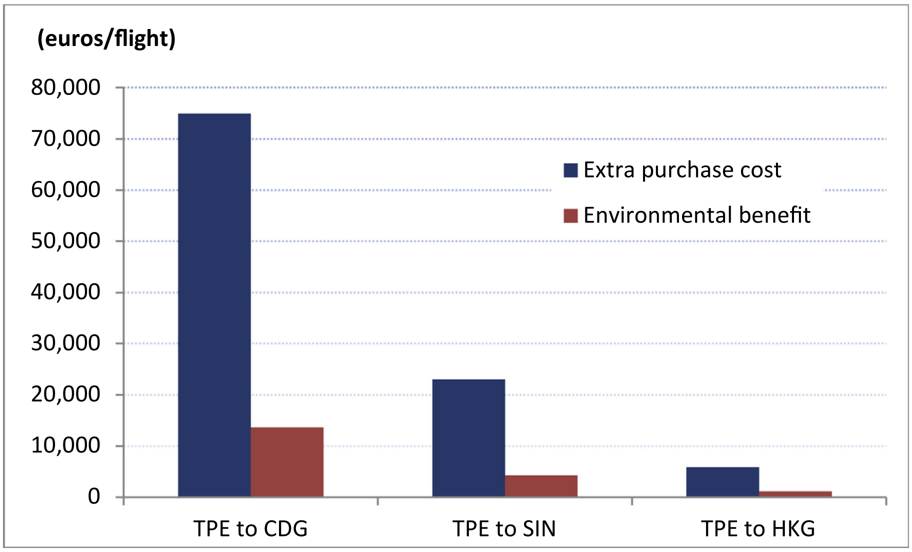

Fig. 3. Extra purchase cost and environmental benefit of using biofuel ~ Base case.

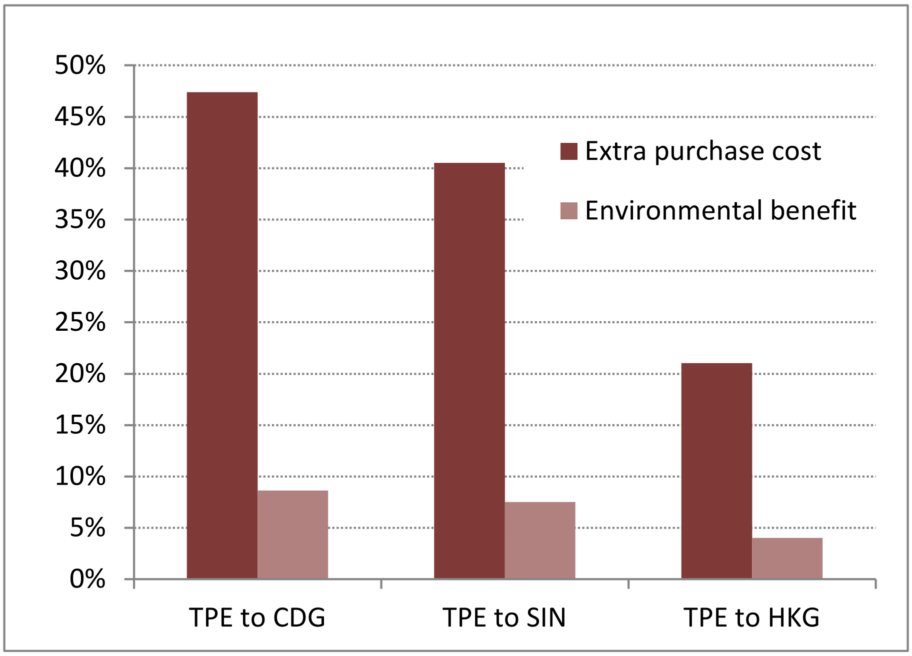

Fig. 4. Comparison of extra purchase cost and environmental benefit with air fares.

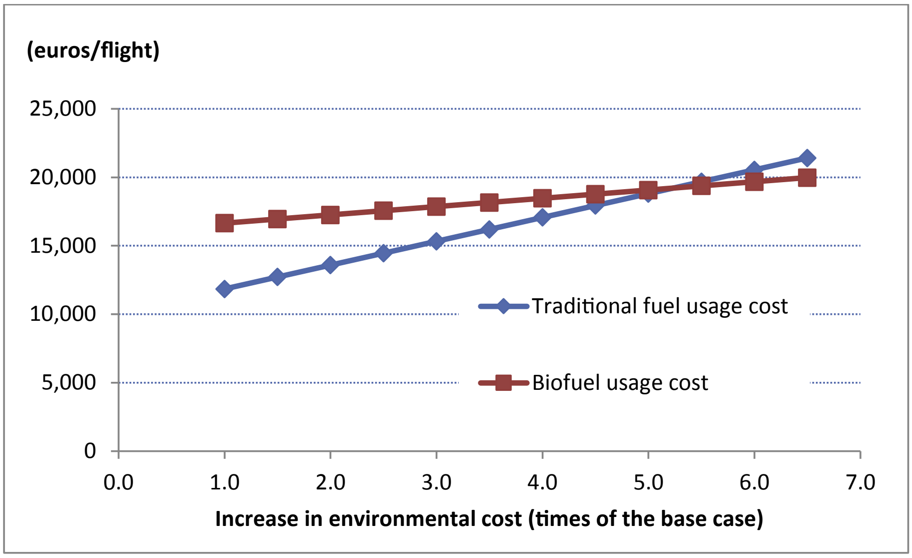

Fig. 5. Sensitivity analysis I: Increase in unit environmental cost.

environmental costs reach five to six times more than the average values used in the base case, the use of biofuel becomes more economical than the traditional fuel. Given that the unit environmental costs of pollutants are highly uncertain (as shown in Table 1), coupled with the increasing speed in implementation of market-based measures in the aviation industry worldwide, this scenario could represent a highly possible future. On the other hand, in the case of CO_2 emissions, the carbon allowances in the European Union Emission Trading System (EU ETS) have traded at a high of around €30 in July 2008 and a low of less than €4 in September 2016 (Intercontinental Exchange, 2017). Unless a market-based measure can be applied to reflect the actual environmental cost of emissions, the use of biofuel will still be an expensive emission abatement option relative to alternatives (Winchester et al., 2013).

With current progress in biofuel production technology, biofuel price is foreseen to reduce gradually in the future. If traditional fuel price stays constant, Fig. 6 illustrates that the biofuel usage cost would be less than that of traditional fuel when the biofuel price is less than US$0.70/litre. This price difference is around 11% more than the traditional fuel price in the base case (US$ 0.63/litre), representing the degree of environmental gain from the use of biofuel.

If the biofuel price remains constant, Fig. 7 shows that when the traditional fuel price is greater than US$0.93/litre, the traditional fuel usage cost will be higher than that of biofuel (the biofuel price is US$1.00/litre in the base case), so the biofuel price is just 8% more than the traditional fuel price in this case. This high fuel price happened from May to July in 2008, when the monthly average price of aviation jet fuel was higher than US$0.99/litre, and even reached US$1.03/litre (US Energy Information Administration, 2016). Note that the increase in traditional fuel price might cause ripple effects on the whole market, hence, the biofuel price might be affected. If the biofuel price is pushed upwards, the threshold of the traditional fuel price would also be higher.

4. Conclusions and recommendations

Since 2008, many of the world's airlines have made over 2000 biofuel flights between them. The main feedstocks used have been

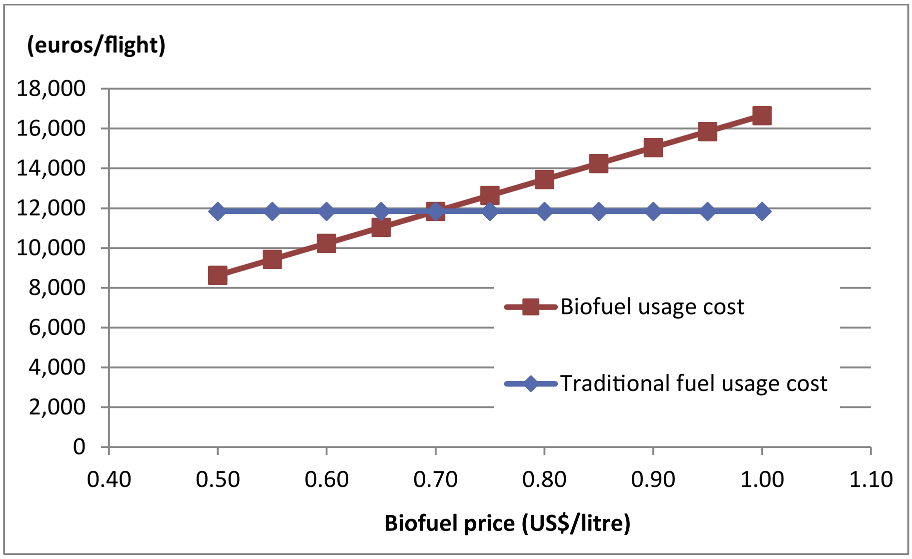

Fig. 6. Sensitivity analysis II: Decrease in biofuel price.

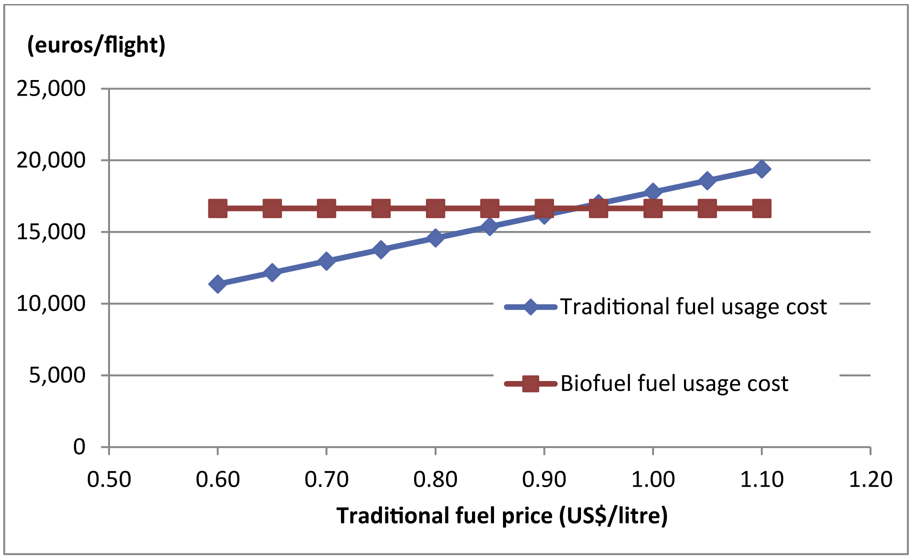

Fig. 7. Sensitivity analysis III: Increase in traditional fuel price.

camelina, algae, used cooking oil etc. This trend continues both through the encouragement generated by government policies and through being one of IATA's four-pillar strategies towards the goal of cutting carbon emissions in half by 2050 compared with 2005 levels, although this has been jeopardised by the recent low oil price.

Global biofuel production has been increasing rapidly over the last decade, but the expanding biofuel industry has recently raised important concerns. In particular, the sustainability of many first-generation biofuels – which are produced primarily from food crops such as grains, sugar cane and vegetable oils – has been increasingly questioned over concerns such as reported displacement of food-crops, effects on the environment and climate change (Lin and Lu, 2014). For the aviation industry, one of the most important aspects is that the use of biofuel has to be sustainable, which means meeting several sustainability criteria. Without being sustainable, the use of biofuel would be just a simple replacement for fossil fuel, which might bring unforeseen negative impacts in the future (GBEP, 2011).

This paper has examined the use of biofuel in the aviation industry, and the key issues in choosing biofuels. It has focused on the analysis of the environmental benefits and purchase cost of biofuels, compared with those of traditional fossil fuel. A cost benefit ratio of more than 5 has been shown for biofuel usage, suggesting that this is not economical compared with traditional fuel, given the parameters applied in this analysis. The sensitively analysis further evaluates the changes in unit environmental costs, biofuel and traditional fuel prices, when the environmental costs are internalised through market-based measures. The results show that when the unit environmental costs are five times higher than the base case or the biofuel price is just around 8–11% higher than the traditional fuel (depending on the parameters in the base case), the use of biofuel is more economical than traditional fuel.

At present, biofuel prices range enormously according to feedstock and production methods. However, with improving technologies and more stable feedstock supply, some long-term supply contracts at comparatively affordable prices are now available (Boyd, 2015). This will certainly bring reaching the threshold for sustainable biofuel use in the aviation industry closer. Furthermore, mechanisms such as EU ETS and ICAO's CORSIA global market-based measure will enable the internalisation of these environmental externalities and should serve as positive incentives for switching to biofuel usage.

This paper has evaluated the environmental benefits of emission reduction, one of the key sustainable issues when choosing biofuels. The research results can be seen as an attempt to evaluate the costs and benefits in monetary values rather than absolute quantification figures. Given that the unit environmental costs vary depending on the damages evaluated and the scope concerned, the values vary extensively in nature. In addition, the actual biofuel combustion emission index might be different depending on the feedstock used. The emission index used in this paper could be improved when the real combustion figures are publicly available.

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List of Abbreviations

AEDT	Aviation Environmental Design Tool
CDG	Paris Charles de Gaulle Airport
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EU ETS	European Union Emission Trading System
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	(US) Federal Aviation Administration
FT	Fischer-Tropsch
HKG	Hong Kong Chek Lap Kok.
HRJ/HEFA	Hydroprocessed Renewable Jet/Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation.
LTO	Landing and take-off
PM	Particulate matter
SIN	Singapore Changi Airport
SPK	Synthetic Paraffinic Kerosene
TPE	Taiwan Taoyuan International Airport

Appendix

Table Emission indices for the aircraft types used in the analysis (g/kg fuel)

Aircraft type*	Take-off	Climb out	Approach	Idle
CO				
B777-300 E R	0.08	0.07	1.98	39.10
A330-200	0.34	0.31	1.23	37.00
HC				
B777-300 E R	0.04	0.03	0.06	4.24
A330-200	0.07	0.07	0.18	9.53
NO_X				
B777-300 E R	50.30	36.00	16.50	5.19
A330-200	45.60	31.70	10.30	4.69

Source: ICAO, 2015.

Note: * The figures are for the engine types used by Taiwanese airlines.

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