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Module 2: Economy

Carbon Policy Sensitivity Test: Appendix 3

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1 Introduction

The most recent analysis of policies to reduce emissions from UK aviation was undertaken by DfT in 2011, *A Marginal Abatement Cost Curve for the UK Aviation Sector: Technical Report (2011)*[1] (hereafter referred to as the DfT MACC report). This appendix refreshes the cost assumptions for biofuel demonstration plants and kerosene (Jet-A1) in the DfT MACC report. The updated costs are provided in Section 2.

Section 3 is a review of key relevant literature since the DfT MACC report was published in 2011. This provides background and some context for the policy levers but does not directly produce any updated costs, with the exception of biofuel demonstration plants.

[1] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4209/mac-report.pdf

2 Cost Updates

2.1 Jet A1 (kerosene) price forecasts

Jet A1 (Aviation Turbine Fuel) is a kerosene-type jet fuel and the most commonly used fuel for commercial aviation across the world. The DfT MACC report used DfT's price projections for kerosene to 2050, which the report states were in turn based on DECC's projections of fuel prices[2]. No detail is given regarding the specific edition of the fuel price projections used.

2.1.1 Update to cost assumption

As part of this update, a regression analysis has been undertaken to explore the past relationship between Jet A1 prices and Brent Crude oil prices, with a view to producing updated Jet A1 price forecasts. The regression used monthly historical time series data from the US Energy Information Administration (EIA) from January 2008 to January 2015.

The analysis demonstrates a strong relationship between the Jet A1 and Brent Crude prices. Therefore the regression analysis has been used to produce updated low, medium and high Jet A1 price forecasts to 2086, using low, medium and high oil price forecasts from the International Energy Agency (IEA). The IEA's low oil price forecasts assume falling oil prices over the period, whilst the medium and high oil price forecasts assume that oil prices will increase. This trend is therefore mirrored in the updated Jet A1 price forecasts.

2.1.2 Summary of updated costs

Table 1 below shows the updated Jet A1 (kerosene) price forecasts.

Table 1: Jet A1 (kerosene) price forecasts: summary of forecasts in the DfT MACC report and updated forecasts

Jet A1 (kerosene) price	Forecast in DfT MACC Report	Updated price forecast (2014 prices)
Low	2014 - £0.25 2030 - £0.27 2050 - £0.27	2014 - £0.51 2030 - £0.48 2050 - £0.42
Medium	2014 - £0.36 2030 - £0.44 2050 - £0.44	2014 - £0.52 2030 - £0.56 2050 - £0.69
High	2014 - £0.73 2030 - £0.82 2050 - £0.82	2014 - £0.54 2030 - £0.62 2050 - £0.80

2.2 Biofuel demonstration plants

There have been a number of successful demonstrations of biofuels being blended with kerosene and used as a "drop in"[3] fuel for aircraft. This lever assumes that the biofuel demonstration projects will increase the take-up of biofuels for aviation and therefore the costs of this lever are the cost of biofuel demonstration plants.

[2] DfT MACC report pg. 68
[3] "Drop in" biofuels are completely interchangeable with conventional fuels and therefore can be used with existing infrastructure.

2.2.1 Update to cost assumption

The total demonstration plant costs are shown in Table 2. These meet the 400m litres/year demand assumption used in the DfT MACC report, which rounds up to forecast demand to the nearest 100m litres/year to allow for downtime. The costs are based upon the Technology Readiness Level (TRL) 7 indicative cost ranges provided by Arup URS Consortium in a study for DfT in 2014[4].

TRL is a relative measure of the maturity of evolving technology and is measured on a scale of 1 to 9. TRL 1 corresponds to basic research on a new invention or concept and TRL9 corresponds to a fully commercialised technology. TRL 6 corresponds to a small scale demonstration plant and TRL 7 corresponds to a full scale demonstration plant.

Table 2: Estimated range of demonstration plant costs to meet 400m litres/year demand

Cost range	Total Investment Cost (£m, 2014)	Cost per plant (£m, 2014)
Lower estimate	654	164
Central estimate	1,636	409
Higher estimate	4,090	1,022

The higher cost estimate in Table 2 could be seen as overly pessimistic, as it is unlikely that all demonstration plants would be at the low end of production capacity yet also with high costs. Given that 20 of these small demonstration plants would be needed to meet the expected demand, it might also be expected that there would be some cost reductions over time. A report by Ecofys, *Biofuels for Aviation* (2013)[5], suggested that there is a progress ratio of 85% with each new plant. This progress ratio relates to general process optimisation and the typical investment cost reduction associated with the industry.

It is therefore considered that the central estimate of costs from Table 2 is the most appropriate.

The assumption in the DfT MACC report that 25% of the plant cost will be publically funded has also been reviewed. The Arup URS Consortium 2014 report states that the publically funded proportion for TRL 7 demonstration plants would be in the range of 10-30%. The report also provides examples of demonstration plants in the EU that have received public funding of between 17% and 18%, and others that have received more than 50%. Given this range, the 25% used in the DfT MACC report appears to be in line with current funding criteria.

2.2.2 Summary of cost updates

Table 3 below shows the updated costs for the Biofuel Demonstration Plants lever.

Table 3: Biofuel demonstration plants: summary of costs in the DfT MACC report and updated costs

Policy lever	Cost in DfT MACC Report	Updated cost (2014 prices)	Key justification for update
Cost per 100m litres of annual biofuel capacity	$250m (£158m)[6]	£409m	Estimates produced for DfT for TRL7 Advanced biofuel demonstration plant costs.

[4] https://www.gov.uk/government/publications/advanced-biofuels-demonstration-competition-feasibility-study
[5] Biofuels for Aviation, http://www.ecofys.com/files/files/ecofys-2013-biofuels-for-aviation.pdf
[6] The sterling equivalent figure shown here was used in the DfT MACC tool spreadsheet

The plant cost is assumed to be the same in the Low, Medium and High policy scenarios, which are set out in the DfT MACC report. The policy scenario does however affect the annual biofuel capacity required.

DECC's high carbon prices[7] have been used in the calculations for fuel cost savings for biofuels.

[7] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

3 Literature Review

3.1 Schäfer et al. (2014), unpublished

The most specific recent analysis of aviation fuel and carbon reduction initiatives is *The Costs for Mitigating CO_2 emissions from Narrow Body Passenger Aircraft – An Analysis for the US Domestic Air Transportation Sector*, by A.Schäfer et al., December 2014. Although the focus is on narrow bodied aircraft and domestic USA activity, there are sufficient parallels to European aviation activity for the paper to offer useful insights.

The paper considers several measures for reducing aircraft-related CO_2 emissions, including those below, which are directly relevant:

Table 4: Relevant measures from Schäfer et al. mapped to the MACC levers

Schäfer reference	Relevant lever
Technology measures - Electric taxiing	Operational incentives
Synthetic Jet Fuels from Second Generation Biomass	Biofuel demonstration plant Mandatory biofuels
Operational options - Single engine taxi - Lateral/vertical/speed inefficiency reduction during cruise	Operational incentives
Airline Business Strategies - Reducing contingency fuel	Operational incentives

The costs estimated by Schäfer et al. (2014) are largely focused on financial costs to firms which are calculated through the fuel cost savings from implementing these measures, for example the airline and ATC (air traffic control) equipage and training costs for implementing single engine taxi. Fuel cost savings are valued using an oil price of $3.1 per gallon[8]. These are then compared to the CO_2 emission reductions from reduced fuel use in order to calculate the cost-effectiveness of each measure. This contrasts to the DfT MACC report which estimated the social benefits of the levers and incorporated carbon prices.

The following conclusions from Schäfer et al. (2014) are relevant to this study:

- All operational measures are cost-effective, along with some airline business strategies (largely higher passenger load factors through reduced flight frequency);
- Of those measures that were not cost-effective, biofuels provided one of the largest potential reductions in CO2;
- The jet fuel price would need to be at least $9 per gallon (three times that of the 2012 level) in order for all considered strategies to be cost-effective;
- For those options that are cost-effective at a fuel price of $3.1 per gallon, capital constraints do not appear to be an issue;
- "In fact, airlines have already stated pursuing all options that we [Schäfer et al.] identified to be cost-effective under such fuel price conditions or have expressed interest in those strategies that are currently under development."

[8] Schäfer et al refer to the $3.1 per gallon fuel price as "currently prevailing fuel prices" and the "2012 jet fuel price".

The assertion that airlines are already pursuing cost-effective measures is not further evidenced within Schäfer et al. (2014) in its unpublished form. However the development of more efficient aircraft (such as the B787 Dreamliner, B737-Max, the Airbus 350 and the A330neo) is the clearest demonstration of commitment by airlines to major investment in aircraft fleets that will help provide savings from fuel reductions. Other evidence for investment in fuel and carbon saving options can be found in Sustainable Aviation[9] reviews[10], airline press releases[11] and the aviation press[12].

Schäfer et al. (2014) have drawn conclusions on the impact that different rates of fleet growth could have on the extent to which the intensity reductions are translated into absolute decreases in CO_2 emissions. Assuming a 2% fleet growth per year, they conclude that 2030 lifecycle CO_2 emissions could be reduced by 10% relative to 2012, if applying the cost-effective measures only. However, with a 3% fleet growth per year, the emission reduction measures are not sufficient to counter emissions from increased activity. In order to reduce CO_2 emissions under this scenario, cellulosic biomass-based synthetic jet fuels would need to be deployed at a scale significantly greater than 5% of all jet fuels consumed in 2030.

The conclusions drawn by Schäfer et al. (2014) are based on a jet fuel price of $3.1 per gallon (in 2010 prices), i.e. the 2012 jet fuel price remaining unchanged. With this price of jet fuel, around three-quarters of the cumulative reduction potential would be cost-effective.

As of 22/05/2015, the jet fuel price was $1.73[13] per gallon in 2010 prices, around half that figure. Recent and forecast oil price changes will have significant implications for the cost-effectiveness of the various measures explored in Schäfer et al. (2014). A lower oil price is likely to reduce the cost-effectiveness of measures.

The following sections consider literature relevant to specific levers.

3.2 Operational measures

Airfield taxiing was previously considered under the ATM efficiency lever in the DfT MACC report but has now been redefined as operational. Relevant literature relating to each of the three operational measures (fuel efficient cruising speeds, airfield taxiing and reduction in contingency fuel) is considered separately in the following three sections. Sources include Schäfer et al. (2014) and are supplemented by other relevant literature.

3.2.1 Fuel efficient cruising speeds

The cruise phase of a flight occurs between climb and descent and generally accounts for the largest percentages of trip time and fuel burn. It therefore provides opportunities for operational mitigation.

[9] Sustainable Aviation brings together main players from UK airlines, airports, manufacturers and air navigation service providers. It is a long-term strategy which sets out the collective approach of UK aviation to tackling the challenge of a sustainable future for the aviation industry.
[10] http://www.sustainableaviation.co.uk/progress-report/
[11] http://www.britishairways.com/en-gb/bamediacentre/newsarticles?articleID=20140416080250; http://www.aa.com/i18n/aboutUs/corporateResponsibility/caseLibrary/protecting-the-environment.jsp
[12] http://www.flightglobal.com/news/articles/analysis-after-three-years-in-service-how-is-787-performing-405814; http://www.flightglobal.com/news/articles/airbus-validates-sharklet-retrofit-for-older-a320s-407321/.
[13] http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx

There are inefficiencies in the lateral, vertical and speed domains during the cruise phase of a flight, but the abatement assessment focuses on speed inefficiencies. Schäfer et al. (2014) and Boeing[14] (2007) consider the cost savings associated with altering cruising speeds to improve fuel efficiency, however there is little information in the literature on the cost of implementing such measures. Schäfer et al. (2014) have provided costs for all three inefficiencies combined (lateral, vertical and speed). These consist of training and equipage costs for the airline and for air traffic control (ATC) and are shown in Table 5.

Table 5: Costs of implementing lateral/vertical/speed inefficiency reduction during cruise

	Airline costs (one-off) £(2014 assumed)/aircraft		ATC costs (one-off) £(2014 assumed)/Airport or ATC	
	Training	Equipage	Training	Equipage
Lateral/vertical/ speed inefficiency during cruise	15,185	24,296	15,185	60,740

These costs are not considered sufficiently relevant to the UK aviation sector, given they relate to the US domestic market and consider narrow-body aircraft only. In the US, there is a different life cycle for aircraft, with narrow-bodied aircraft being retired much later than in the UK. Therefore the costs are not fully transferable to all aircraft operating from a UK hub and are not used in the cost update.

3.2.2 Airfield Taxiing

This operational measure incorporates two options:

- Single engine taxiing; and
- Electric taxiing.

Schäfer et al. (2014) provide some indicative costs for implementing congestion management measures and for single engine taxiing. Although numerous other references have been reviewed, no robust additional information on costs has been identified.

Table 6: Costs of implementing surface congestion management and single engine taxiing

	Airline costs (one-off) £(2014 assumed)/aircraft		ATC costs (one-off) £(2014 assumed)/Airport or ATC	
	Training	Equipage	Training	Equipage
Surface congestion management	15,185	0	75,925	303,700
Single engine taxiing	15,185	0	0	0

There are various options for electric taxiing systems – Wheeltug[15], Taxibot[16] and EGTS (electric green taxiing system)[17]. However, there is no publically available cost information for these.

[14] http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_07/article_05_1.html, http://www.boeing.com/commercial/aeromagazine/articles/qtr_2_07/article_05_1.html

[15] http://wheeltug.gi/ . WheelTug is a ground propulsion system for aircraft. It involves putting two electric motors in the nosewheel. It was announced in January 2015 that Air Transat would provide access to an aircraft for development and testing purposes. http://www.marketwired.com/press-release/air-transat-provides-aircraft-for-wheeltug-development-and-testing-1981111.htm

[16] http://www.taxibot-international.com/ . The TaxiBot is a hybrid-electric aircraft tractor which taxies aircraft with turned-off engines to the runway. As of February 2015, the TaxiBot is being used in real flight operations at Frankfurt Airport with Lufthansa planes. http://www.lufthansagroup.com/en/press/news-releases/singleview/archive/2015/february/20/article/3439.html

[17] http://www.greentaxiing.com/ . The EGTS system involves the installation of an electric motor on each of the main landing gear driving inboard wheels, which are powered by the auxiliary power unit (APU) generator. It allows the aircraft to push back from the gate without a tug tractor and taxi without the use of the main engines. Airbus and various airlines have signed memorandums of understanding (MoU) with EGTS International.

As above, the costs are not considered sufficiently relevant to the UK aviation sector, given they relate to the US domestic market and consider narrow-body aircraft only. In the US, there is a different life cycle for aircraft, with narrow-bodied aircraft being retired much later than in the UK. Therefore the costs are not fully transferable to all aircraft operating from a UK hub and are not used in the cost update.

3.2.3 Reduction in contingency fuel

There are international and local regulations which determine the amount of contingency fuel that an aircraft must carry. Reducing the amount of fuel that an aircraft carries reduces the take-off weight and therefore the amount of fuel used, with a corresponding reduction in CO_2 emissions. Schäfer et al. (2014) provide some estimates relating to the amount by which contingency fuel can be reduced.

If reducing contingency fuel allows schedule reliability and safety to be maintained, it is an airline's decision and can be implemented at zero additional cost. If an aircraft needs to divert due to insufficient contingency fuel, then there are costs associated with passenger, equipment and crew re-accommodation as a result of the diversion. However, no estimates for such re-accommodation costs are present in Schäfer et al. (2014). No additional sources of costs for potential impacts of contingency fuel reduction have been identified at the time of writing.

3.3 Biofuel demonstration plants

Gaining a realistic estimate of the capital costs of demonstration plants is challenging. This is partly due to the diversity of technologies, which have different cost profiles depending on the technology readiness level, complexity and investment risk. These are dependent on a range of factors including future feedstock costs. There is also limited publically available cost and capacity data for existing and planned demonstration plants, with misleading and conflicting information published, which cannot be readily validated.

There are many pathways to producing biofuels suitable for blending with aviation fuel. These pathways use a range of conversion technologies, and for each conversion technology there are also a range of potential feedstocks. Sustainable Aviation's *Sustainable Fuels UK Road-Map* (2014)[18] provides a summary of the conversion technologies:

- Hydro-processed esters & fatty acids (HEFA) and Hydrotreated Vegetable Oil (HVO);
- Fischer-Tropsch (F-T);
- Synthesized Iso-Paraffinic (SIP) routes;
- Alcohol-to-jet (ATJ) routes; and
- Hydrotreated depolymerised cellulosic jet (HDCJ).

There are commercial scale plants operating that use a subset of processes to produce renewable fuels from biomass feedstocks, although these primarily produce biodiesel for road transport. Currently a small fraction of these commercial plants are used for aviation biofuel production.

[18] http://www.sustainableaviation.co.uk/wp-content/uploads/SA-SAF-Roadmap-FINAL-24-Nov.pdf

The *Sustainable Fuels UK Road-Map* (2014) observes that "*approximately 10% of current output could be destined to aviation fuel"* and that it is *"technically feasible to configure plants to produce 60% aviation fuels"*. However, it is currently more commercially viable to generate biodiesel than biofuels for aviation. There are also concerns over the availability and sustainability of feedstocks currently used these commercial plants. Alternative feedstocks for the HEFA process, such as algal oil, are technically feasible, but are currently being used in plants which are only at pilot or demonstration stage, and therefore have not yet been demonstrated to be commercially viable.

The *Sustainable Fuels UK Road-Map* (2014) report contains a list of existing and planned biofuel plants in Table A5.7. However, on further investigation, it was difficult to verify the current status of these projects using alternative sources, with some of the listed plants found to have been delayed or cancelled. The challenge to progress planned projects has also been reported elsewhere, for example the IEA reports that the "*first advanced biofuels projects get shelved as they struggle to secure investments*" (IEA[19], 2014). A further source of cost information is provided by Arup URS (2014). The cost information contained in the report is based on more detailed studies of existing and planned demonstration plants, and although it focuses on advanced biofuels in general (rather than aviation biofuels specifically), the plant cost information is directly transferable.

The indicative cost range for plants incorporating technologies at demonstration plant stage provided by Arup URS (2014) is shown in Table 7.

Table 7: Indicative Advanced Biofuel Demonstration Plant Costs

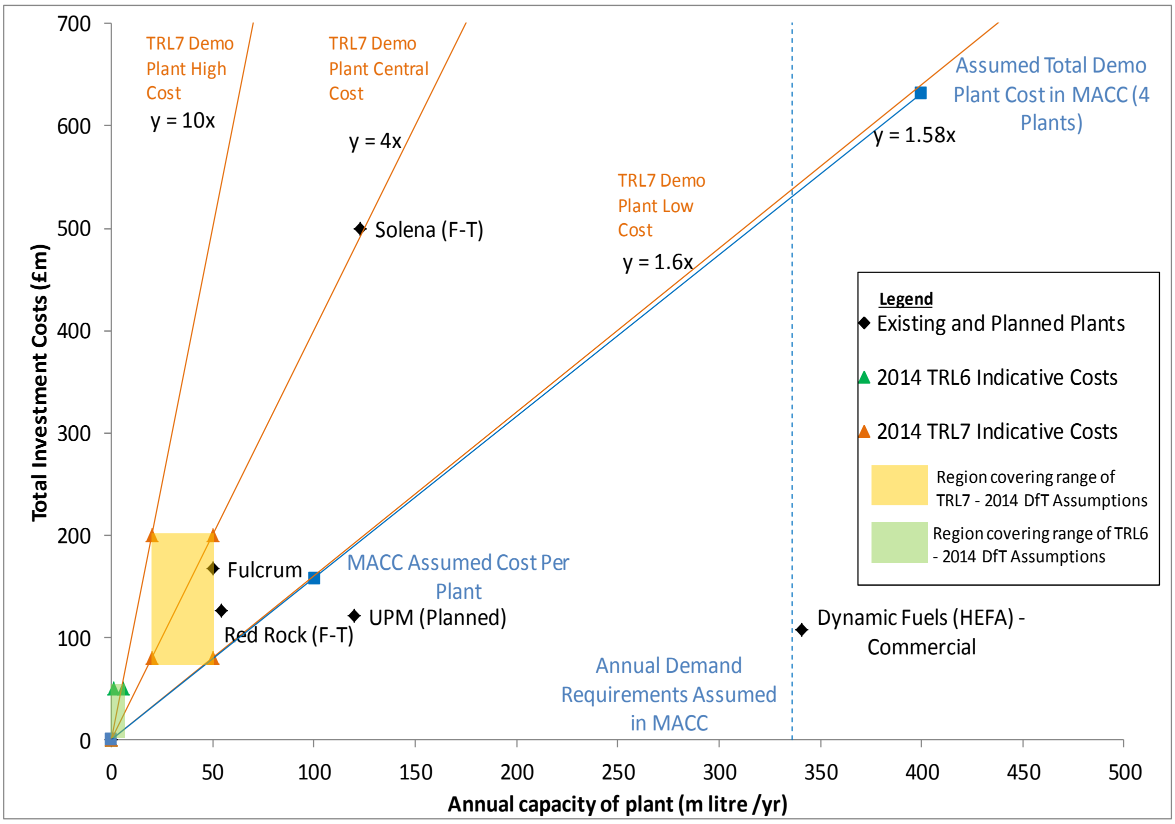
Technology Readiness Level (TRL)	Capacity (m litres per year)	Total Investment Costs £m (2014)
TRL 7 (Full-scale demonstration plant)	20-50	82-205
TRL 6 (Small-scale demonstration plant)	1-6	Up to 51

These ranges of demonstration plant capital costs have been plotted on Figure 1, which also shows the DfT MACC cost assumptions and the costs for existing and planned plants. As previously discussed, the existing and planned plant costs are not reliable but are shown for comparison. Using the 2014 TRL7 indicative cost ranges, three cost-capacity relationships are also shown on Figure 1:

- Lower estimate (combining the lower cost estimate with the high production estimate);
- Higher estimate (combining the higher cost estimate with the low production estimate); and
- Central.

[19] Renewable Energy Medium Term Market Report 2014, summary presentation available at http://www.biofuelstp.eu/spm6/docs/charles-esser.pdf

Figure 1: Plant capital costs against annual capacity



3.4 Mandatory biofuels

As highlighted in a broad range of recent academic and industry sources, including a 2014 update by the IEA, the long-term evolution of biofuels prices is highly uncertain in the absence of a post-2020 framework. This is particularly relevant for the advanced biofuels industry, where perceived investment risk is high.

The costs of producing biofuels for aviation are currently considerably more than for fossil-fuel derived fuels. In the *Sustainable Fuels UK Road-Map* (2014), it is reported that fuels derived using the HEFA process (the only biofuel producing process currently at commercial scale) cost 2.5 times more than standard aviation fuels. Similar findings are presented in other literature, such as Winchester et al (2013)[20], which states that aviation biofuel needs a subsidy of £1.72[21] per gallon for price parity. However, it does highlight that the cost of feedstock and the competition for land use is a significant component of this, suggesting that the required subsidy would reduce to £0.22[22] if crops were grown on otherwise fallow land. These are assumed to be 2013 prices.

In a report authored by a consortium including Qantas, Shell and SKM, *A feasibility study of Australian feedstock and production capacity to produce sustainable aviation fuel* (June 2013), it is estimated that biojet fuel would cost approximately

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[20] http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt238.pdf
[21] The report quoted a figure of US $2.69. This was converted to Sterling using the Bank of England's annual average spot exchange rate for 2013.
[22] The report quoted a figure of US $0.35. This was converted to Sterling using the Bank of England's annual average spot exchange rate for 2013.

£0.31-0.62[23] per litre (or £1.40 to £2.80 per gallon) more than conventional fuel, while Ecofys (2013) reports that biofuels are 2-4 times more expensive than fossil fuel jet fuels. The figures in the consortium report are assumed to be in 2013 prices.

While the values in literature may vary, it is clear that there is currently a price premium for biofuels. The trajectory of this in the future will depend on a range of factors. In Sustainable Aviation's *CO_2 Road-Map*[24] there is a section on the economics of biojet which highlights the fact that "*biojet must become economically viable and cost-competitive over the long-term compared to kerosene from fossil fuel sources*."

Over the longer term, there is an expectation that biojet fuel will become cost competitive due to the following factors:

- Expected increase in fossil fuel prices, due to both demand and supply pressures;
- Application of carbon pricing in global economies, with increasing costs of carbon;
- Reducing biojet unit production costs due to economies of scale and technology learning;
- Lower feedstock costs;
- Reduced capital costs as technology develops; and
- Application of carbon pricing in global economies, with increasing costs of carbon.

[23] The report quoted a figure of AUS$1.00-1.50. This was converted to Sterling using the Bank of England's annual average spot exchange rate for 2013.
[24] http://www.sustainableaviation.co.uk/wp-content/uploads/SA-CO2-Road-Map-full-report-280212.pdf

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